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SPACE SHUTTLE TECHNOLOGY CONFERENCE

**Volume I - Operations, Maintenance,
and Safety**

**AIAA/NASA Conference
Phoenix, Arizona
March 16, 1971**

This volume contains papers dealing with
Ground Operations, Flight Operations and
Safety - presented at the Space Shuttle
Technology Conference, held at Phoenix,
Arizona, March 16, 1971.

FOREWORD

The prospect of undertaking a reusable launch vehicle development led the NASA Office of Manned Space Flight (OMSF) to request the Office of Advanced Research and Technology (OART) to organize and direct a program to develop the technology that would aid in selecting the best system alternatives and that would support the ultimate development of an earth-to-orbit shuttle. Such a Space Transportation System Technology Program has been initiated. OART, OMSF, and NASA Flight and Research Centers with the considerable inputs of Department of Defense personnel have generated the program through the efforts of several Technology Working Groups and a Technology Steering Group. Funding and management of the recommended efforts is being accomplished through the normal OART and OMSF line management channels. The work is being done in government laboratories and under contract with industry and universities. Foreign nations have been invited to participate in this work as well.

The Space Transportation System Technology Symposium held at the NASA Lewis Research Center, Cleveland, Ohio, July 15-17, 1970, was the first public report on the program. The symposium on which this publication is based was held at Pheonix, Arizona during the week of March 15, 1971 and was the second report in the areas of Biotechnology as well as Operations, Maintenance, and Safety. The Symposium goals are to consider the technology problems, their status, and the prospective program outlook for the benefit of the industry, government, university, and foreign participants considered to be contributors to the program. In addition, they offer an opportunity to identify the responsible individuals engaged in the program. The Symposium sessions are intended to confront each presenter with his technical peers as listeners.

Because of the high interest in the material presented, and also because the people who could edit the output are already deeply involved in other important tasks, we have elected to publish the material essentially as it was presented, utilizing mainly the illustrations used by the presenters along with brief words of explanation. Those who heard the presentations, and those who are technically astute in specialty areas, can probably put this story together again. We hope that more will be gained by compiling the information in this form now than by spending the time and effort to publish a more finished compendium later.

A. O. Tischler
Chairman,
Space Transportation System
Technology Steering Group

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INTRODUCTORY PAPER

N71-36123

SPACE SHUTTLE OPERATIONS, MAINTENANCE AND TECHNOLOGY INTEGRATION

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NASA Headquarters, Washington, D.C.

INTRODUCTION

As the subject of this paper implies, we on the Space Shuttle program have a unique opportunity to build and operate the "707" of space transportation systems. The idea of a two stage fully reusable aircraft/spacecraft system is not new. Over a decade ago, NASA had accomplished this feat by mating the X-15 with its booster, the B-52 as shown in Figure 1. By using this method, NASA was able to mate, fuel the X-15 with hydrogen-peroxide, man the system, launch and fly 199 flights up to altitudes of 354,200 feet and speeds up to mach 6.7 and recover both stages in a safe efficient manner. The technology requirements for facilities, operational support, logistics implications, crew and passenger mix, mission capability, maintenance and checkout operations, and abort and recovery operations are overviewed in this paper.

PROGRAM REQUIREMENTS THAT EFFECT OPERATIONAL TECHNOLOGY

At this point in time, the Shuttle program is in the preliminary design phases of the selected configurations preparing for the 9 month technical "data dump." Figures 2 and 3 show examples of the selected configuration. Figure 4 shows the current schedule and how the phase B Shuttle activity phases with phase C/D Shuttle engine development and technology activities. As phase B activities have progressed, operational requirements have been refined to the point where Shuttle vehicle and engine configurations and sizing have been determined. Figure 5 shows the main engine characteristics currently in phase C design. Concurrently with the above activities the wind tunnel programs at the various government and contractor facilities are continuing to verify the design and configurations selected.

With the "honed down" requirements emerging from phase B trade study activities, the third round of Shuttle program iterations can begin. NASA expects to start phase C design work in FY 1972.

FACILITIES

Shuttle missions, present programs, cost and safety requirements shape and form the total Shuttle facility framework. Figure 6 shows a conceptual Shuttle operational area. The ideal situation for the Shuttle would be to have an optimum positioning of the final assembly, horizontal and vertical flight test, maintenance and launch areas of the

X-15 WITH HYPERSONIC RAMJET

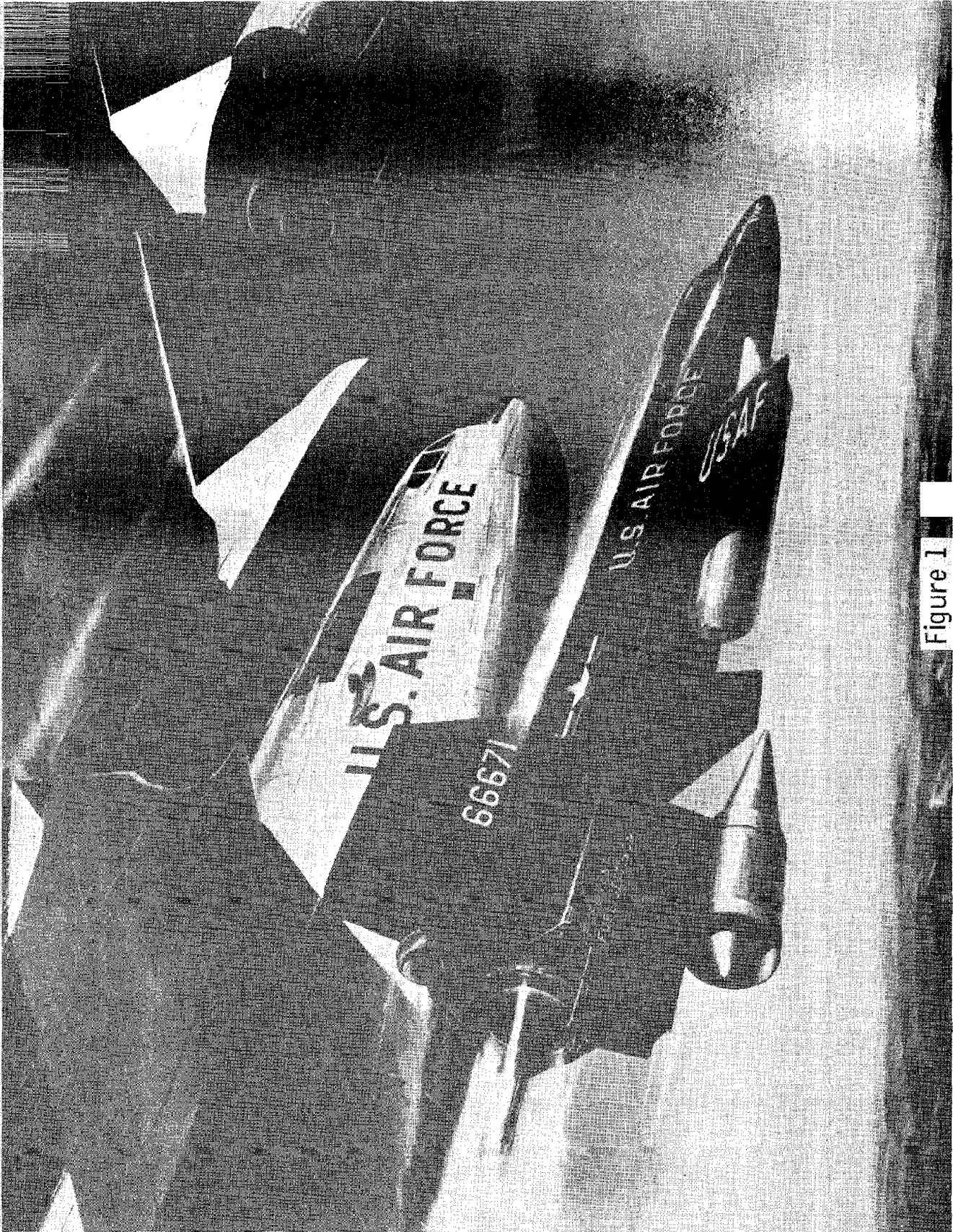


Figure 1

HIGH CROSS RANGE SYSTEM

DRY WEIGHT (LB)	ORBITER	BOOSTER
226,400	226,400	511,000
LANDING WEIGHT (LB)	264,700	533,000
GROSS WEIGHT (LB)	836,000	3,764,000
GLOW	4,600,000	

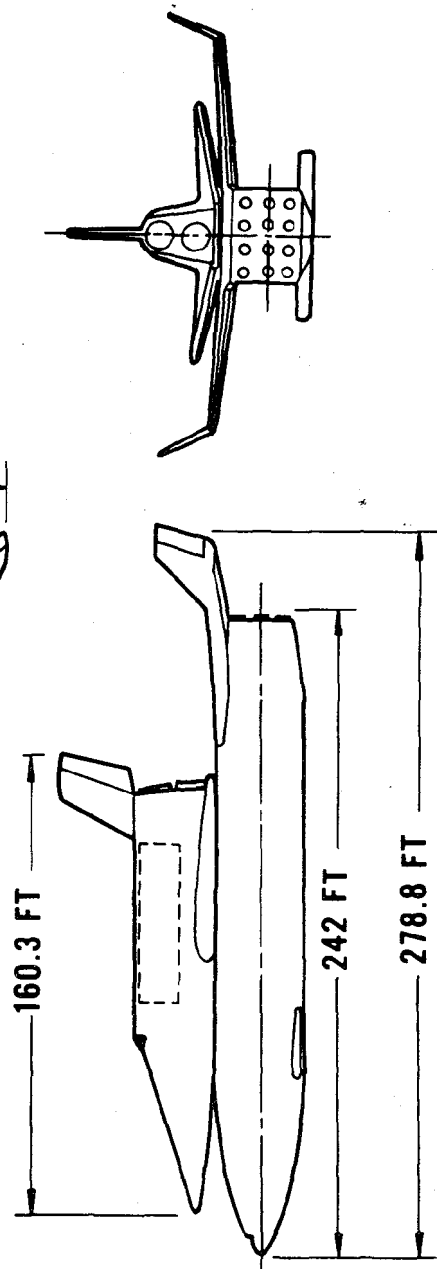
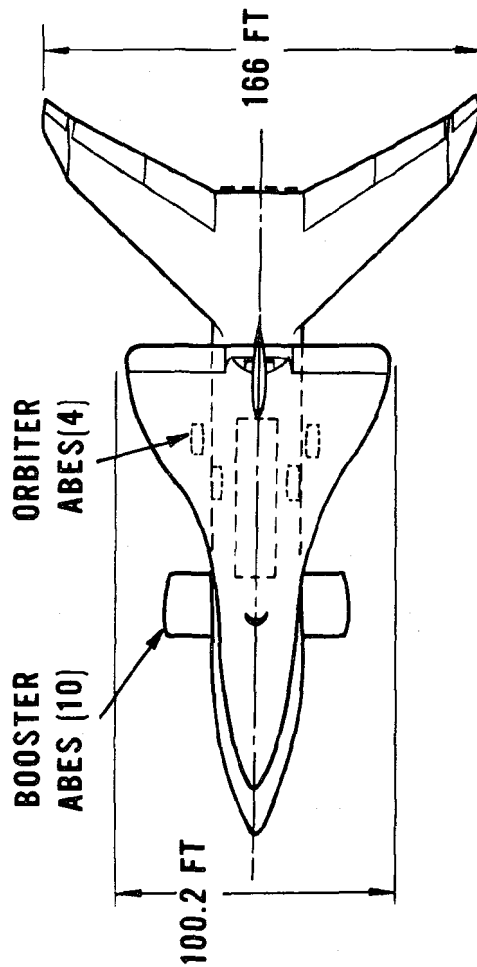


Figure 2

HIGH CROSS RANGE SYSTEM

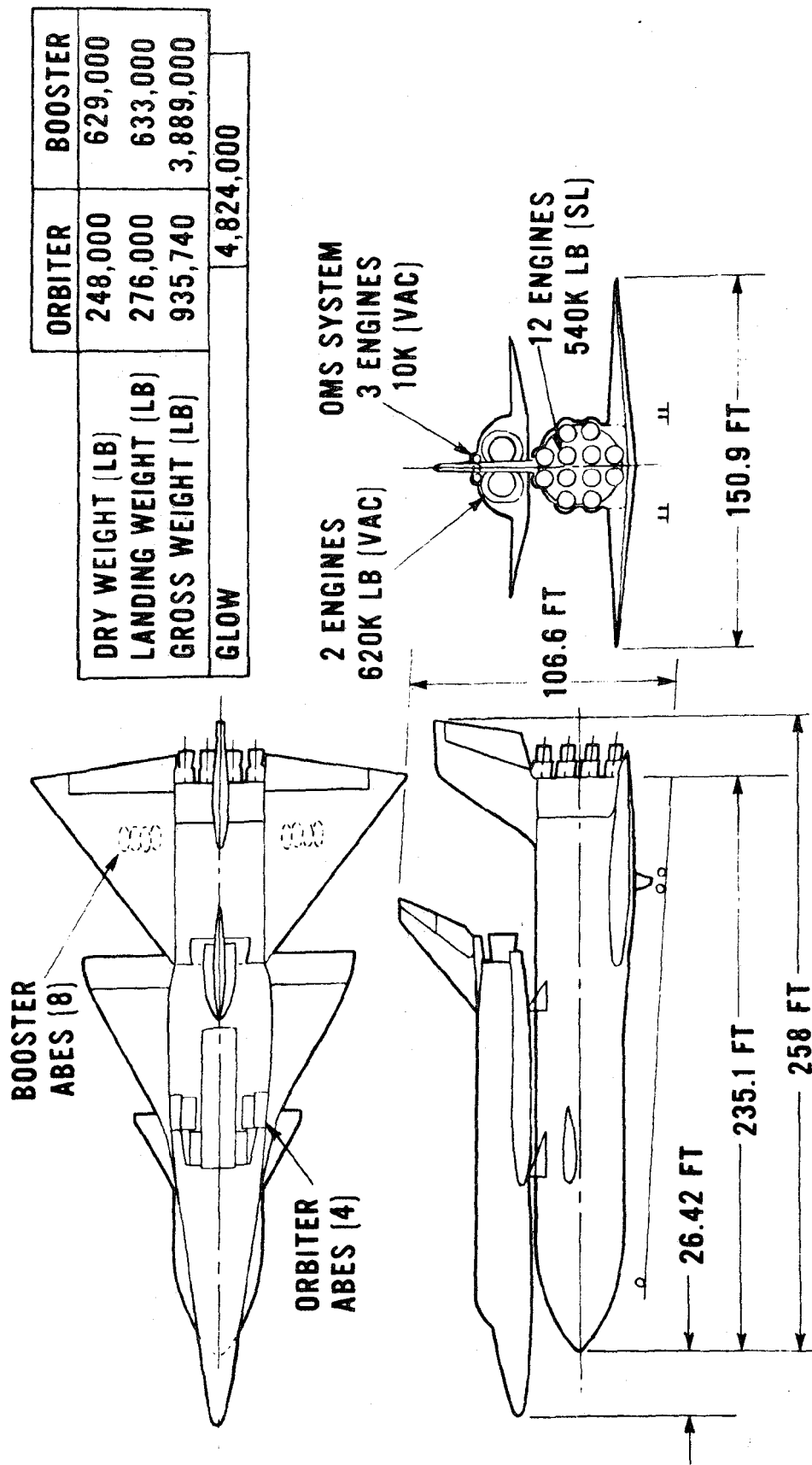


Figure 3

SPACE SHUTTLE PLANNING SCHEDULE

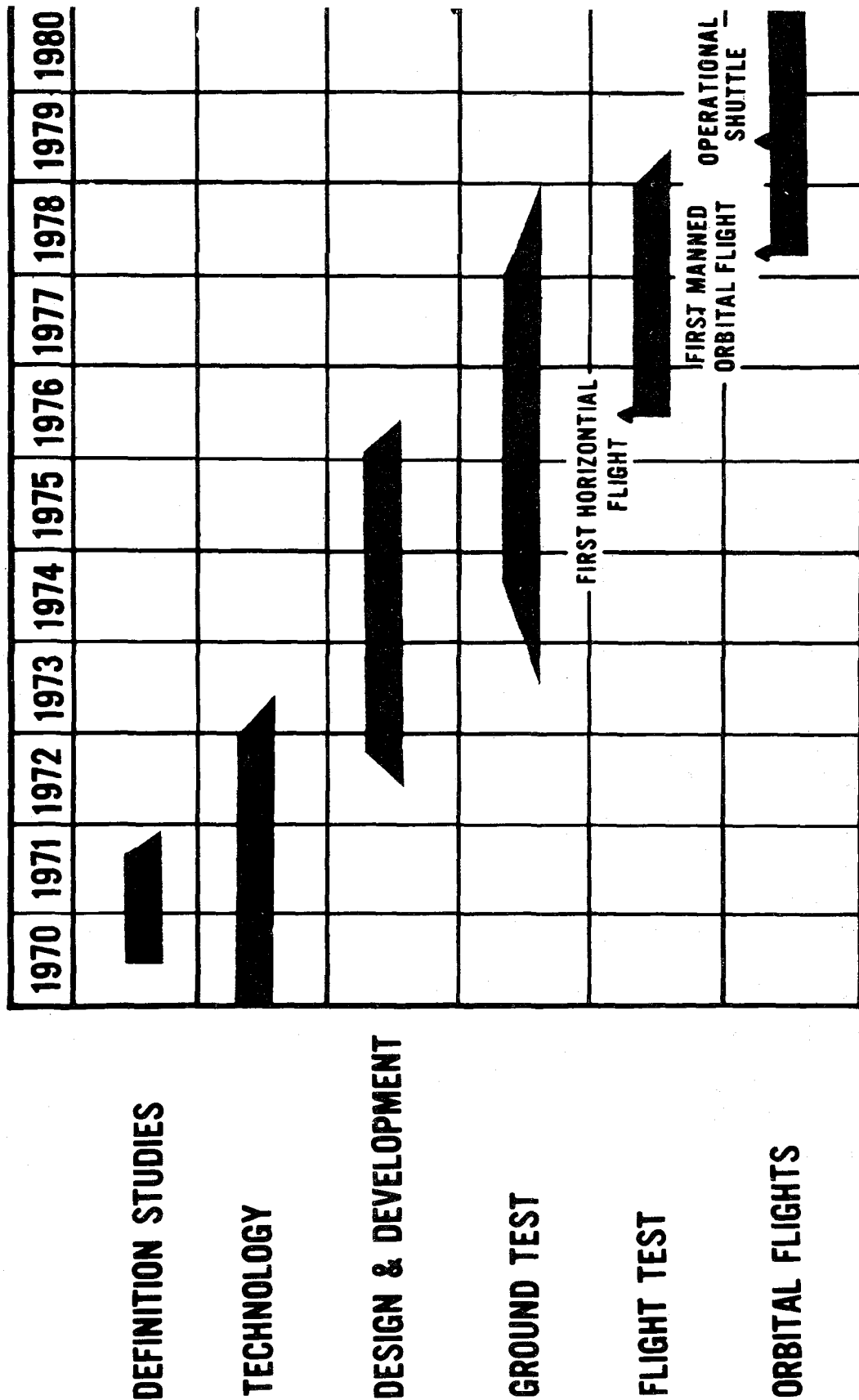


Figure 4

SPACE SHUTTLE MAIN ENGINE CHARACTERISTICS

- LIQUID HYDROGEN /
LIQUID OXYGEN
- 400,000 LBS. (182,000
KGS.) THRUST LEVEL
- BELL NOZZLE
- HIGH PERFORMANCE
- REUSABILITY
- LOW COST OPERATION
- LONG SERVICE LIFE
- THROTTLEABLE
- MINIMUM MAINTENANCE

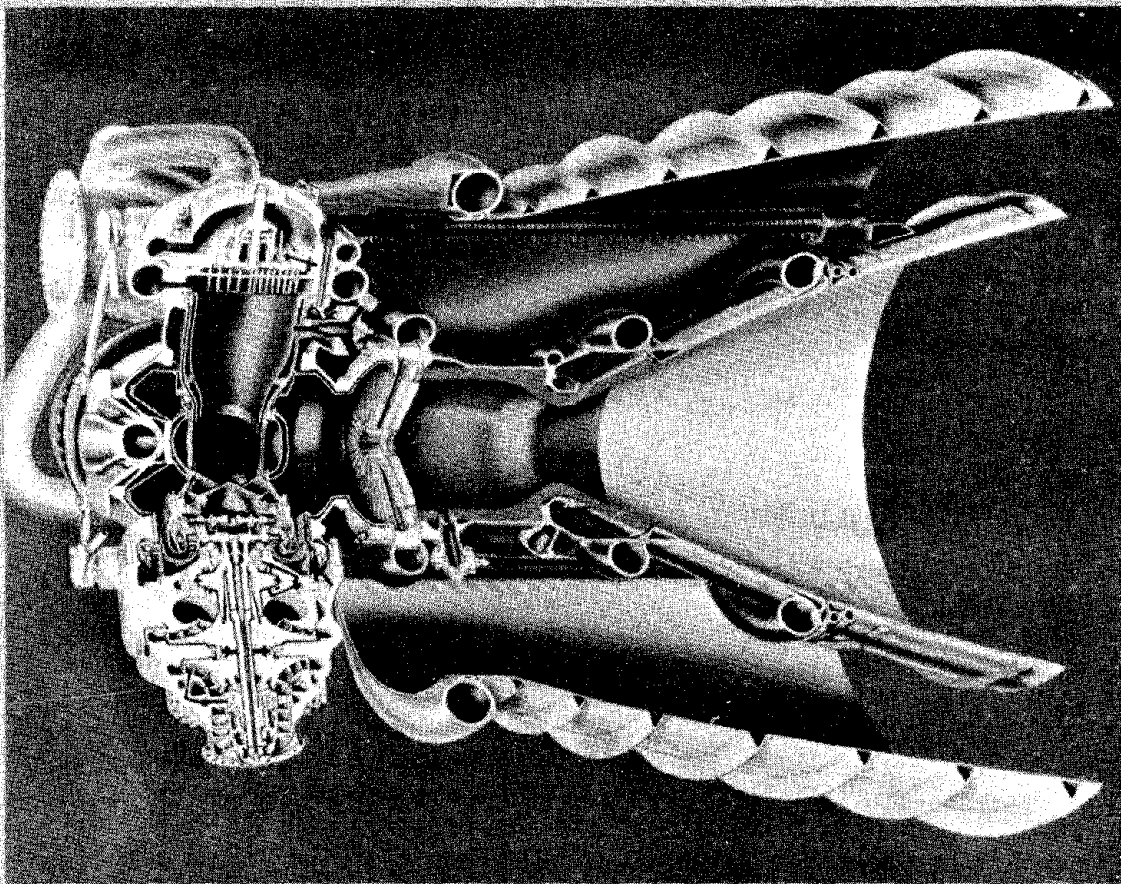
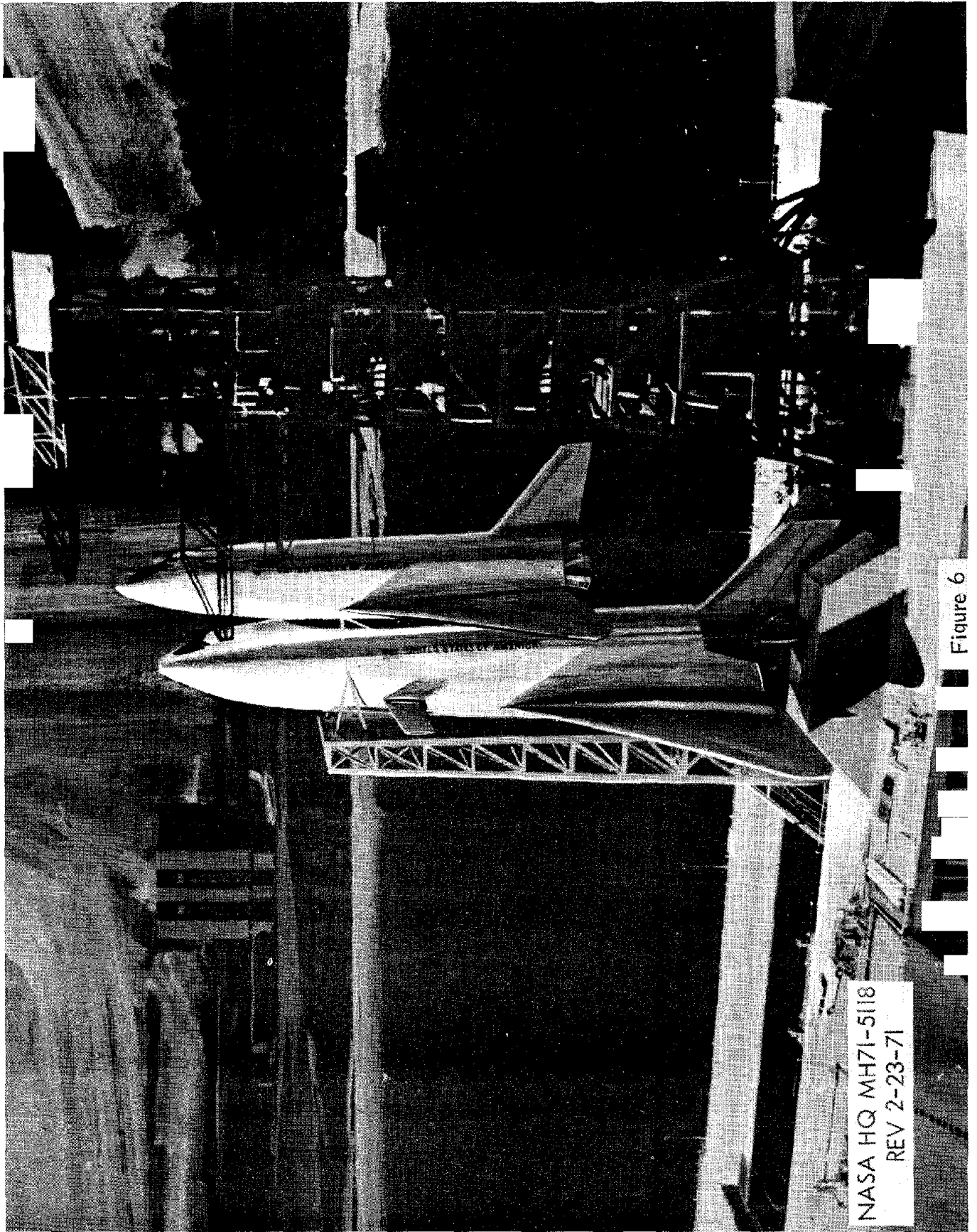


Figure 5

NASA HQ MH/70-6864
8-31-70



NASA HQ MH71-5118
REV 2-23-71

Figure 6

Shuttle booster and orbiter vehicles with as little new construction of facilities as possible. This, of course, has been and is an important trade study. So important in fact, that it can be a significant cost factor in design of the vehicles. The total integration of all phases of Shuttle facilities requires that test and operations technology be integrated at an early date into Shuttle vehicle and test design.

SAFETY

Underlying the total Shuttle and facility design effort is the element of safety. A major requirement for the Shuttle is airline type flight operations and that means intact abort with the crew and passengers. Another major requirement is that the Shuttle have a once around abort to continental United States capability and a possible return to base. Depending on launch site location and mission inclinations, aborts downrange vs aborts to orbit are also being considered. This means that over-flight of populated areas have to be considered as well as low ascending flights over foreign territories. To forestall actual aborts the Space Shuttle vehicle is being designed with very high safety standards. Standards that are similar to SST levels. In general, fail operational/fail safe concepts are used for the structural portions of the vehicle while fail operational/fail operational/fail safe is being designed into Shuttle avionics systems. Ground support systems should also match these guidelines so that the total system conforms to the desired safety level. Also of concern is determining how to advance Apollo pre-launch and launch operations technology from an R&D activity occurring two times a year to a routine once a week airline type activity. NASA has a major requirement to safely fuel the Shuttle vehicles with approximately 3.6 million pounds of cryogenic propellant within two (2) hours. This is a result of an important space rescue requirement. Further, in a normal mission, launch and flight operations are now concerned with handling semi-trained passenger-scientist/technicians in a safe expedient manner. This means some kind of standard operational-safety training for some yet undetermined time prior to a launch to assure passenger suitability for space travel. NASA currently has safety technology studies in work. Some of these technology studies are: Liquid propellant; Explosion analysis; Space Shuttle safety and operations margins engineering analysis; Launch azimuth abort and safety; Hydrogen filled system safety; Spacecraft fire protection; Hydrogen fire detection system, etc.

LOGISTICS

With the advent of the STS, NASA must change from a pure R&D activity to an operational activity. This means that new methods must be found to logistically support all activities of the Shuttle. Some logistic activities required for the Shuttle are:

1. Passenger handling
2. Cargo handling before launch and after landing
3. Fuel storage and servicing
4. Parts supply
5. Payload advanced conditioning and checkout handling, and security.

As mentioned previously, passenger and payload handlers have to be trained well in advance to handle their tasks. This means a pipeline of payloads has to be established for normal and emergency operations. This can be likened to airline operations of normal, deferred and immediate cargo handling. Much preplanning will be required to smoothly operate the Shuttle. This means during Shuttle design, NASA has to constantly bear in mind logistic integration into Shuttle operations. Some of the studies currently in work for logistics technology are: Space cargo handling; Man-Machine integration/simulation of crew and cargo transfer and docking; Support systems for both conditioned and gravity-deconditioned passengers; payload handling, etc.

MAINTENANCE AND CHECKOUT

NASA maintenance and checkout activities presently are confined to R&D one-time usage procedures. New technology is required to reduce long checkout periods down to a matter of hours. Now the Shuttle designers must closely integrate rapid checkout features into the vehicle and GSE. Again the airline concept of autonomous operation has to be borne in mind. Present airline maintenance and checkout technology must be used as a basis for NASA to change thinking from one-time usage to repeated usage all at low cost. Refurbish and maintenance concepts for rocket vehicles are new. NASA will have to integrate new technology for non-destructive testing and possibly go into the "on-condition" maintenance concept that airlines have been using for several years. This means that NASA might not use the TBO concept, but instead, use the "leave-it-alone" principle. For reusable rocket engines this means an entirely different viewpoint with new design oriented toward building into the engines a refurbish and maintenance capability. Figure 7 shows a space Shuttle main rocket engine schematic. New boroscope techniques, etc., will be needed for fast economical turnaround. Shuttle useful life of ten years will require the use of new operational technology developments to accomplish this goal.

Some of the maintenance and checkout studies in work are: Structural integrity assessment techniques; Rapid loading of cryogenics and gases; Leak detection techniques; Redundancy checkout techniques; Bearings and seals development; Non-destructive testing techniques for flight readiness verification; etc.

OPERATIONS

Launch operations of the Shuttle combines the use of facilities, safety, logistics, maintenance and lastly, checkout. Figure 8 shows the Shuttle vehicle at launch. The concept of on-board checkout is being pushed by NASA and is a prime design consideration to reduce time and costs. Checkout before and after erection, in a matter of hours, is a great technology challenge. To start with, during the flight test phase, checkout will understandably be slower but as experience and procedures are refined and by the completion of the ten vertical flight test launches, checkout should be fairly rapid. However, now is the time to integrate checkout technology into Shuttle design.

SPACE SHUTTLE MAIN ENGINE

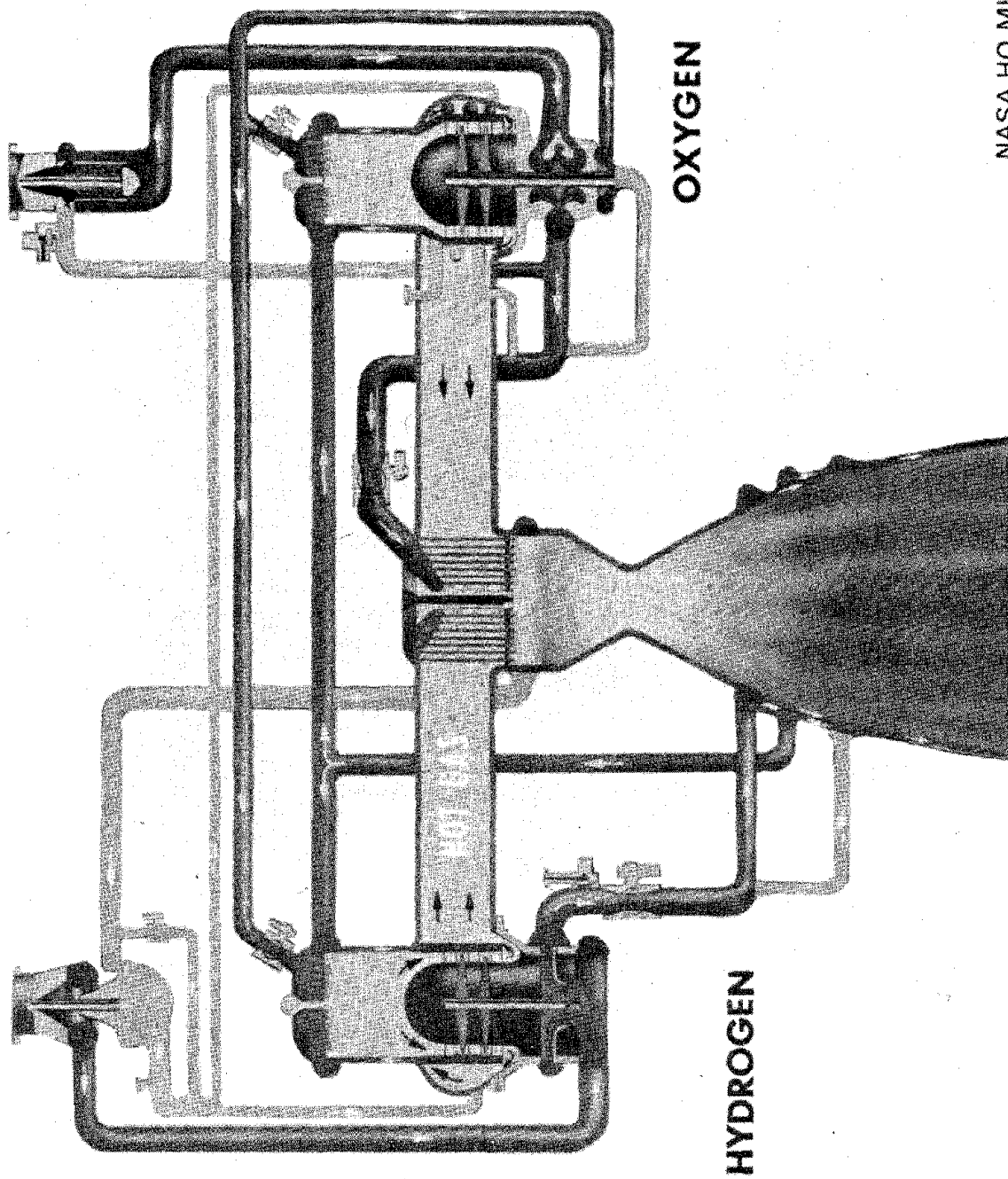
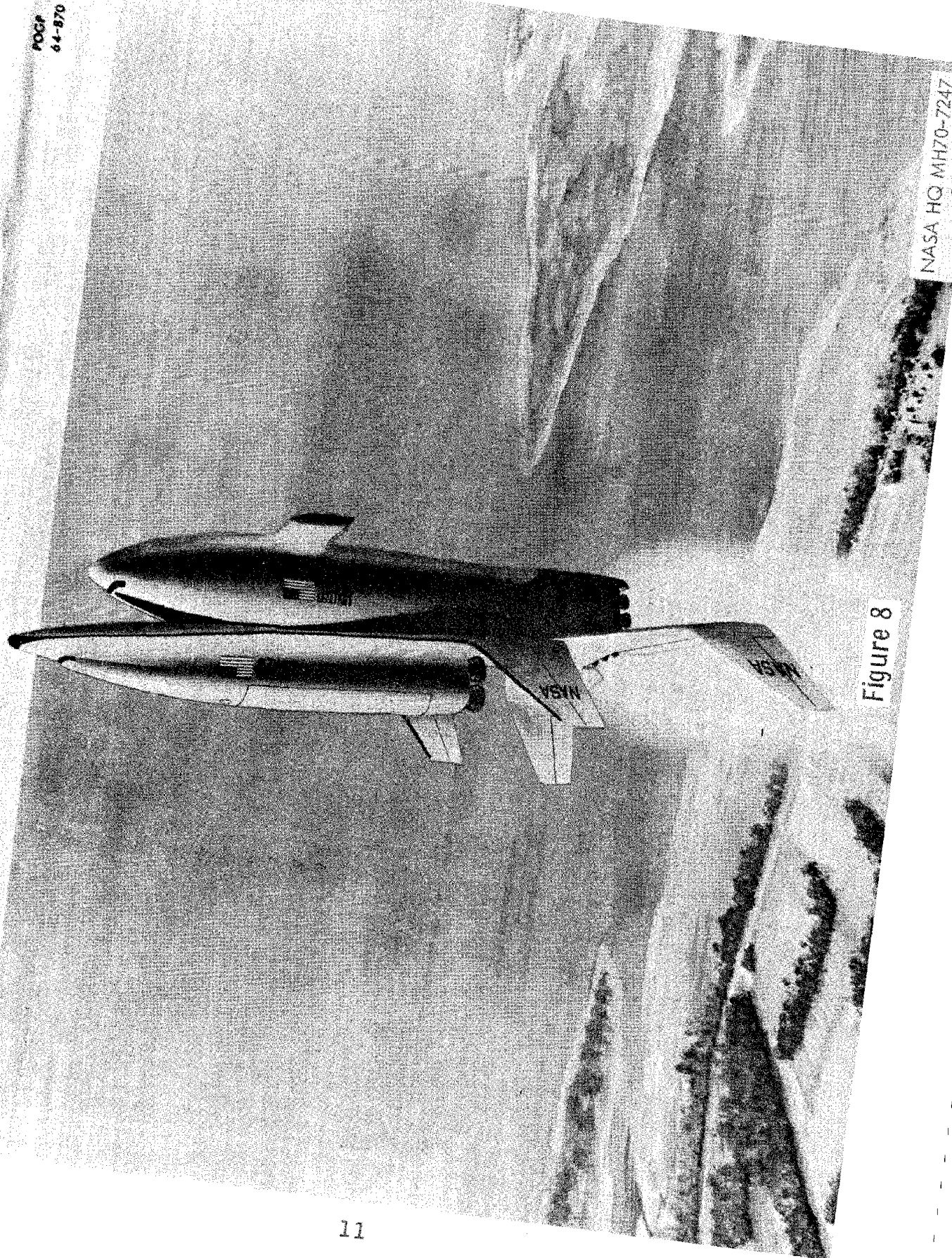


Figure 7

NASA HQ MH71-5173
2-3-71

POGP
64-870



NASA HQ MH70-7247
10-15-70

Figure 8

Flight operations will also have to be simplified in some areas and increased in others. With an autonomous operational requirement for the Shuttle, communication with the ground should not be any more stringent than an airliner. Probably in the early launches, temporary communication gear will be used but later removed as operations become more sophisticated and confidence in the system is obtained. This would be gear used locally during the flight test program. Hopefully, from a cost standpoint, there would be very little extra to remove. Mostly TM channels, etc., would be removed and on-board autonomous equipment utilized to the fullest extent. Thus ground operations during flight would be reduced to a minimum. Unique operational technology developments are needed to keep operational costs low. A trade has to be made using existing versus new operational tracking equipment so that only costs chargeable to the Shuttle occur.

Some of the many operations oriented technology studies in work are: Terminal approach and landing visibility envelopes; Auto pilot handling qualities; Flare and decrab, INS/ILS smoothing; Operational studies; Test and flight engineering oriented man/machine language; Three landing arresting systems testing programs with FB-111 and B-52 aircraft up to 300M ft-lbs energy absorption.

CONCLUDING REMARKS

The Shuttle program does pose unusual unsolved opportunities for NASA as well as industry in all areas, but the integration of operations, maintenance and safety technology into Shuttle design is where a great payoff will occur for the Space Shuttle program. Thus the concept of an economical fully reusable space transportation system can be achieved and could well alter the future of world space operations.

N71-36194

GROUND OPERATIONS

ANALYSIS OF APOLLO LAUNCH OPERATIONS EXPERIENCE

James J. Hart

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INTRODUCTION

When I first was asked to give a presentation of about 25 minutes on the experience gained on the Apollo Program that was applicable to the Shuttle Program, I was completely stumped as to what to say, but once I started, I found that there was a mountain of data available and to say what needed to be said in 25 minutes would be most difficult. Anyway, one thing led to another and what I will present to you I hope you will find both interesting and worthwhile.

SHUTTLE MISSION OBJECTIVES

Early in the Space Shuttle Program when the goal of reducing the transportation cost of space flight by at least an order of magnitude was established, it became apparent that in addition to cost savings due to reusability, something more was needed. We needed to find different ways of going about the business of launch operations which would take advantage of our experience on the Apollo Program. In addition to reducing cost, other desired goals established for the Shuttle Program such as a two-week turnaround, 48 hour rescue capability, and the capability to launch within two hours from a standby status; and certainly a launch rate of 75 flights per year demands that both hardware innovation and operational changes be made. This is not to say that what has been done in the past or is presently being accomplished on the Apollo Program is wrong or ineffective because with a record for the Saturn Program of 22 successful launch vehicle missions out of 23 on the most complicated program the world has ever known says to us that we did most things right. The reason we need to develop and operate the shuttle differently is because the mission of the shuttle is different from Apollo. When we started discussing the new goals on the Shuttle Program and how we, as an operational Center, could do our part to effect the changes in operations and to make significant suggestions and impacts on conceptual designs and decisions that have operational implications, we first needed to fully understand the situation drivers in our present operation and how these things applied to the shuttle. See figure 1.

Additionally, we needed to identify design features of the Apollo hardware, applicable to the Space Shuttle Program, which resulted in operational difficulties.

To gain this information many studies were initiated utilizing the experience of launch operation personnel at KSC and I would like to discuss with you some of the results of this work.

- **REDUCE TRANSPORTATION COST**
- **REUSABILITY**
- **2 WEEK TURNAROUND**
- **48 HOUR RESCUE CAPABILITY**
- **2 HOUR COUNTDOWN**
- **75 LAUNCHES PER YEAR**
- **HARDWARE INNOVATIONS**
- **DIFFERENT TEST METHODS**
- **OPERATIONAL CHANGES**

Figure 1

PROCEDURES STUDY PERFORMED

Since all work performed at KSC on flight hardware and ground support equipment is performed using pre-planned written procedures, it was decided that one systematic method for analyzing our present operation was to review every procedure performed during a vehicle processing from arrival of the stages to liftoff. Obviously, this was a task that no one person or small group of people could accomplish. It was therefore decided that the best way to perform this study was to prepare a questionnaire that would be completed by the people that were responsible for the running of the procedures since they know more about a procedure than anybody else.

A questionnaire was prepared. Not all of the information on the questionnaire was directly applicable to the Shuttle Program, but because we were going to perform this rather massive study, we added a few questions to gain information that can be used on the remaining Apollo Program and upcoming Skylab Program to simplify our operations and reduce the number of procedures performed.

The questionnaire was made up in a form so that the answers to the questions could be transferred into punch cards for computer processing. Two programs were written to process the data. The first program selects the data. The second program takes the data selected by the first program, formats a report, and provides a total count of all questionnaires in each report.

I should explain that the procedure study is not complete and the items discussed will be about the Launch Vehicle (Booster) and its associated ground support equipment only. There will be no discussion of the spacecraft or technical support procedure study because we have not completed their assessment.

PROCEDURES QUESTIONNAIRE PREPARED AND CIRCULATED

Some of the information that we felt we should know about our operation and attempted to find out during this study are listed below:

1. How many tests do we perform on the airborne equipment?
2. How many tests do we perform on the ground equipment?
3. Why do we perform this test?
4. Who requires this test to be performed?
5. What are the major time contributing factors in the running of this test?
6. How many procedures are performed that are not test but are operations (such as unloading a stage from a barge, erecting the vehicle on the LUT, and installing ordnance)?
7. How many preventive maintenance, overhaul or refurbishment procedures do we perform?
8. How many servicing procedures (such as propellant loading and filling the IU water accumulator) do we perform?
9. What specific hardware changes could be made to achieve operational improvements in performing this test?
10. Can we eliminate this operation or combine it with another operation to achieve a saving?

With this background on the procedure study we can now discuss some of the results and recommendations based on the study.

TYPES OF PROCEDURES SURVEYED

The first question we asked on the questionnaire was "Which of the following type procedures does this questionnaire cover?" (See figure 2.) It was aimed at finding out the purpose of the procedures that are performed at KSC. By the way, for those of you who might wonder what the difference is between a test procedure and an operation procedure, let me give you a couple of examples.

The Integrated Systems Test and Flight Readiness Test are test procedures and are run to measure systems performance, while Vehicle Erection and Filling the LOX Storage Tank are operations. The results of this question are as follows: of the total of 1400 procedures conducted by the Launch Vehicle personnel, there are 811 test procedures, 531 operations procedures, 162 maintenance and overhaul procedures, 91 servicing and 68 refurbish procedures. I should warn you to be careful when you use these numbers because one procedure may be strictly a component level test procedure that takes 30 minutes to perform while at the other extreme is a CDDT test that involves almost every person in Launch Operations and takes over 100 hours to complete. The significant point to be gained in the numbers is this, when people talk about the many procedures performed at KSC to process a vehicle, they must understand that about 43% of all the procedures are used in other than test work.

In addition, the number of test procedures is further reduced to 685 when you subtract the 126 standby or contingency type procedures. Since I have mentioned contingency procedures, let me say that in any operation, we feel that there has to be contingency type procedures and the more you have, the faster you can recover from an abnormal situation whether this be an emergency or abnormal maintenance problem. On the Shuttle Program, hopefully we will have enough information in a data bank to make real time type decisions on almost any problem that may arise from emergency safing procedures to how to repair and/or replace a component.

QUESTION NO. 1

WHICH OF THE FOLLOWING TYPE PROCEDURE DOES THIS QUESTIONNAIRE COVER?

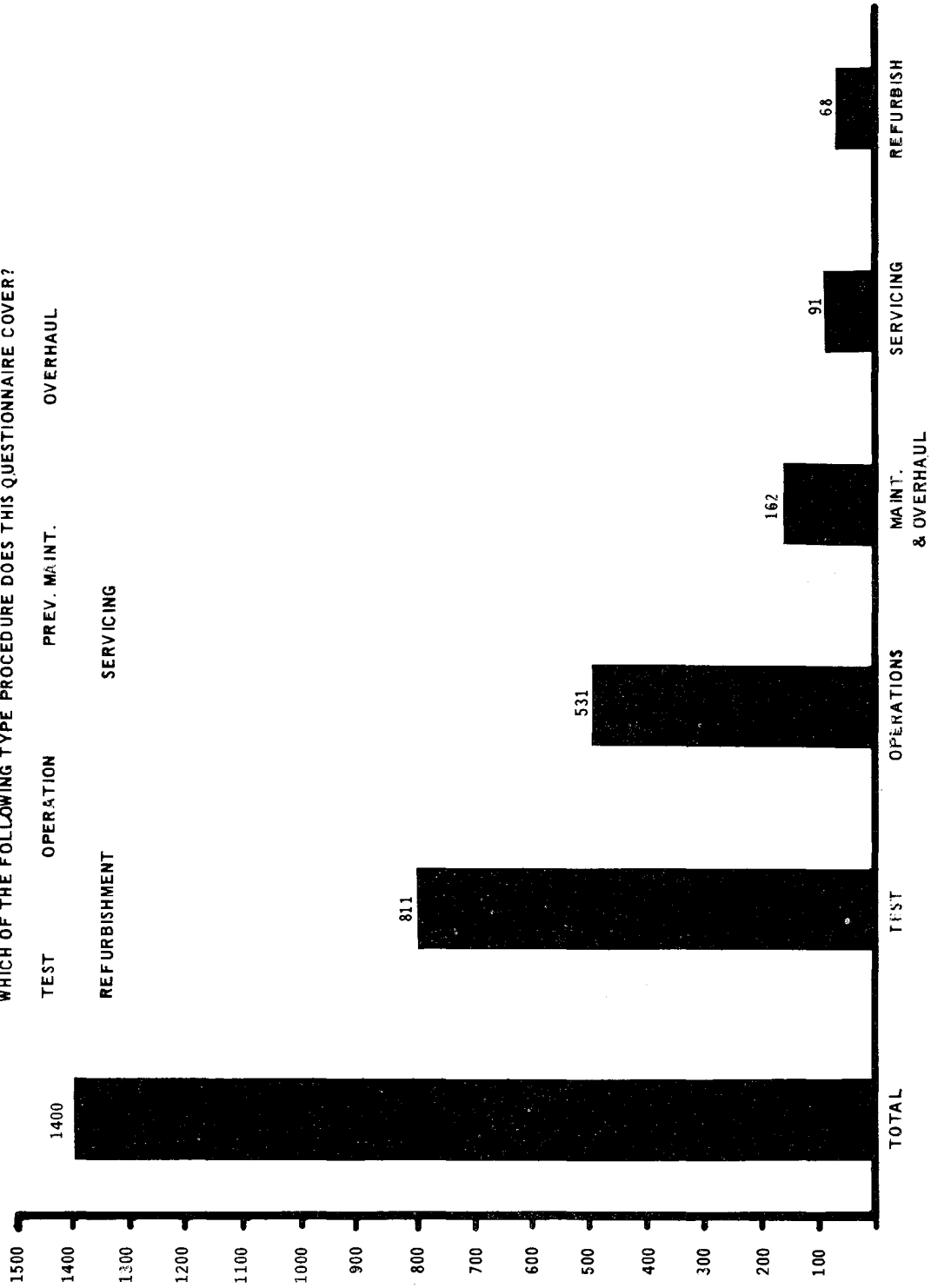


Figure 2

COMPARISON OF AIRBORNE VS. GROUND PROCEDURES

The second question, "What type hardware does this procedure involve?" was intended to find out how many procedures are used for airborne equipment only or ground equipment only, or was used for both airborne and ground systems together. The results are shown in figure 3. There are 333 airborne only procedures, 807 ground only and 260 combination airborne and ground procedures. The significant point here is that there are almost 2-1/2 times as many ground procedures as airborne. This information should highlight the fact that much effort will be required on the Shuttle Program to reduce the number of ground procedures and operations cost associated with the ground systems. On the Apollo Program, the ground system almost always played the supporting role with very little emphasis placed on the number of people required to operate the ground systems, but if you truly want an efficient low cost operation, then the total system - ground and airborne - and the number of people required to operate these systems, must be carefully planned. Neither the airborne nor ground system should unnecessarily penalize the other but should be designed to operate as a total system.

On the Shuttle Program, we are striving for things like vehicle autonomy and minimum ground support equipment which should improve the relationship of ground versus airborne, but as the next two figures show, not all of us feel the same way.

QUESTION NO. 2

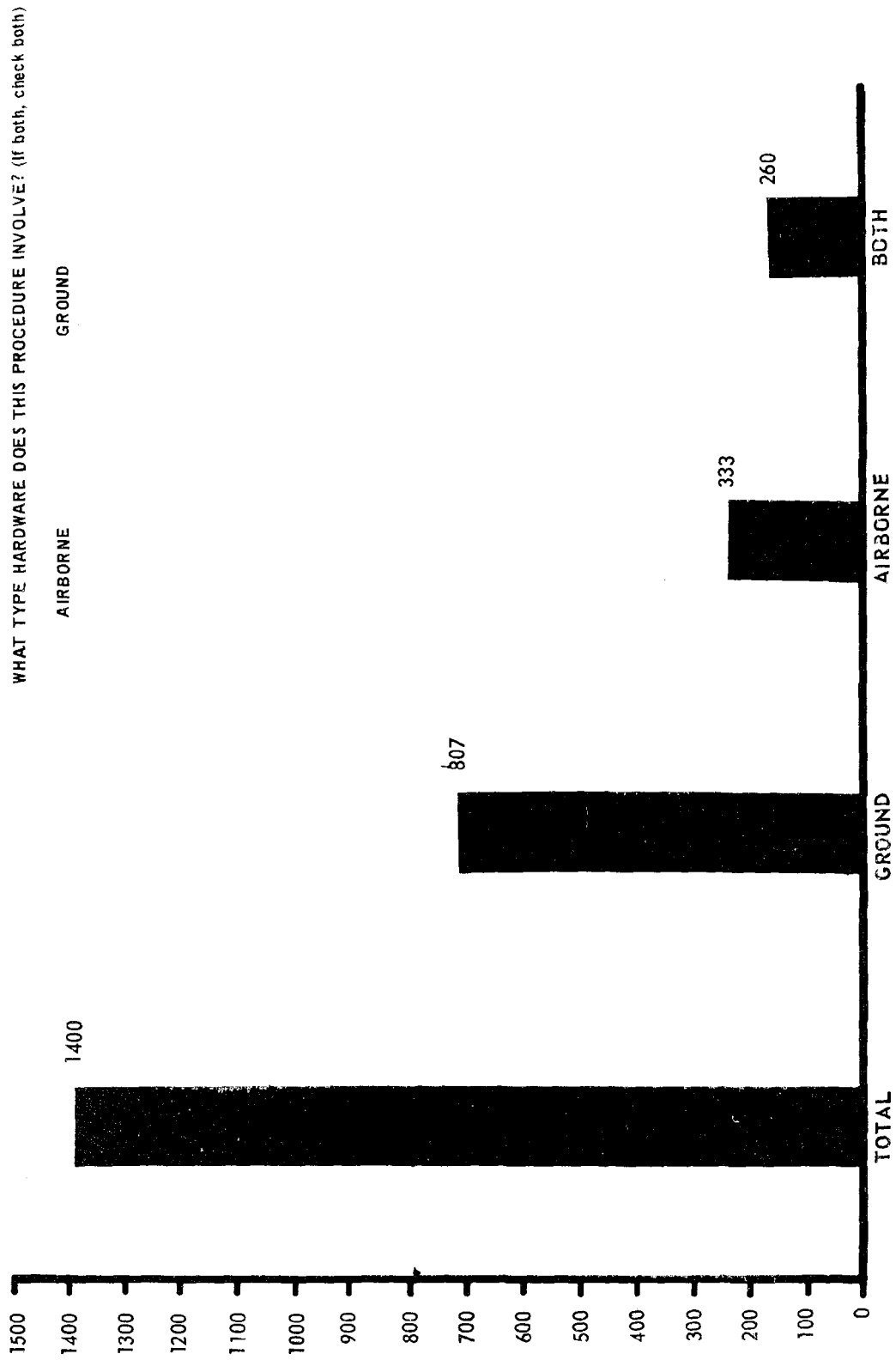


Figure 3

SHUTTLE DESIGN CONSIDERATIONS

This figure really needs no explanation except to say that there are some people who feel that if it weighs anything, it doesn't belong on the vehicle. See figure 4. You can't get low cost operations if you let these people always win and carry that idea too far.

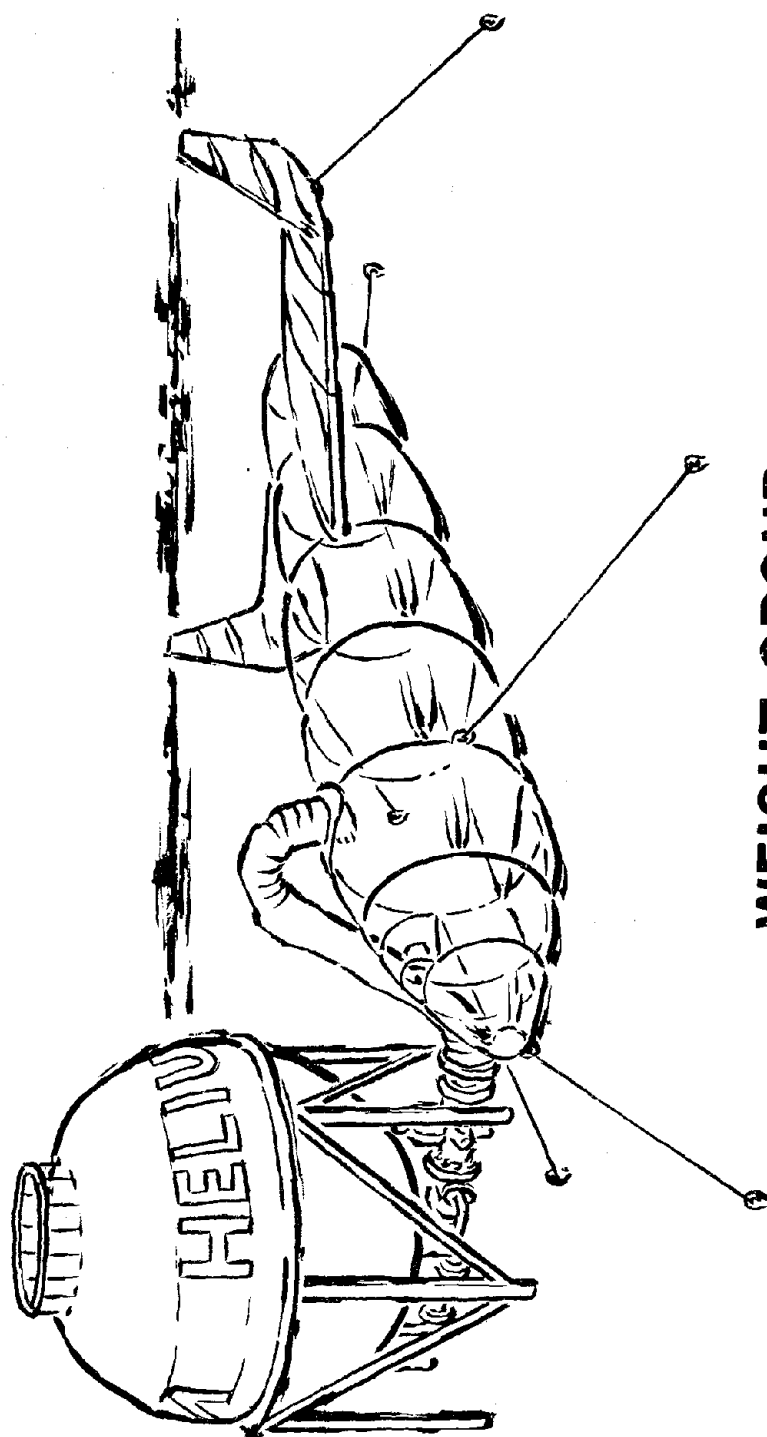


Figure 4

MORE DESIGN CONSIDERATIONS

Again, for some reason, it seems to me that anything the engine people ask for - things like ground hydraulic servicing units, and ground environmental conditioning units - they get. See figure 5. Obviously, there are needs placed on the ground system that are requirements and cannot be served any other way, but to achieve low cost ground operations, each of these needs should be thoroughly reviewed.

By the way, there is a series of 15 cartoons like the past two figures and to show you that I am not picking on anyone in particular, I'll show you how we in Launch Operations would like to see the vehicle. See figure 6.

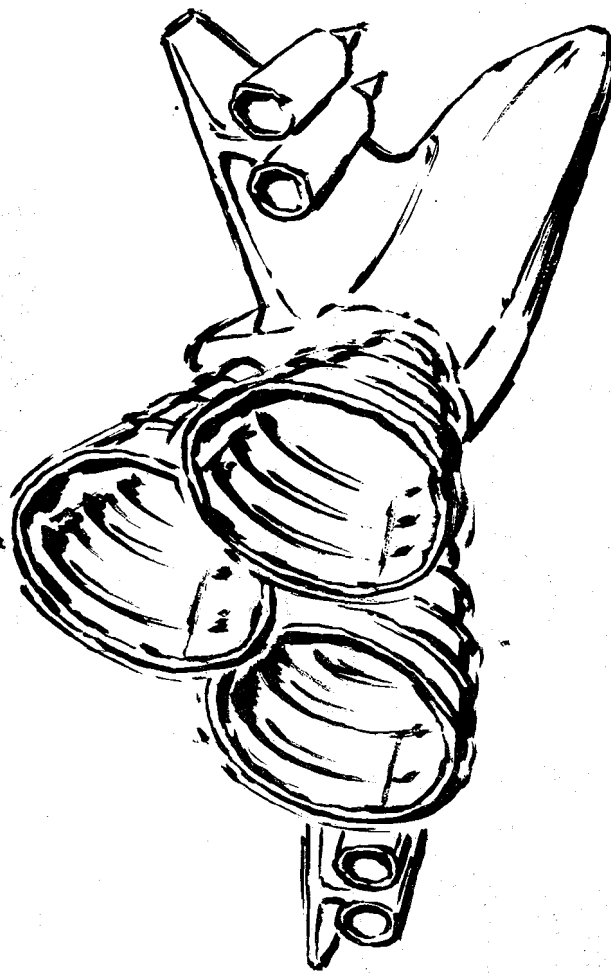
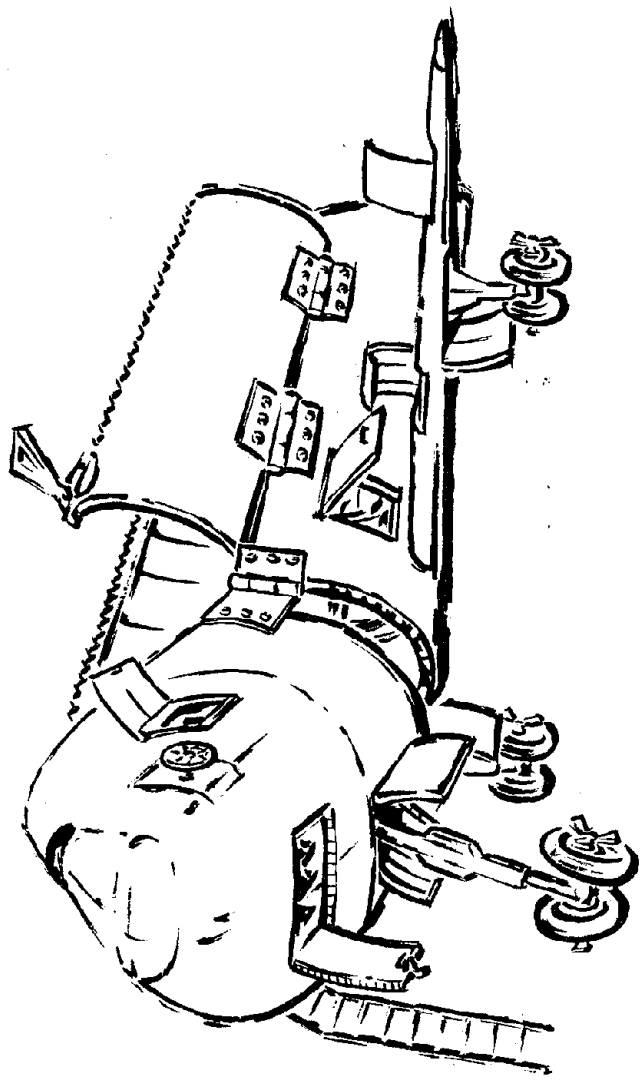


Figure 5



SERVICE GROUP

Figure 6

FREQUENCY OF TESTING NECESSARY ON REUSABLE EQUIPMENT

The next question, "If the equipment that is being tested was reusable (i.e., space shuttle) would this test be required each time the equipment is used for a launch?" This poses a very significant question about the reduction of tests and operations due to a reusable vehicle. See figure 7. Of the 333 airborne procedures, there were only 178 procedures that would be required each launch while 155 procedures would not be required on each launch if the vehicle was reusable. This is a reduction of about 47% due to reusability. The significance here is that if you can get a reduction of this amount for equipment that is designed for a one shot operation, then you can expect a much larger reduction on equipment that is designed with reusability in mind.

Of the 155 procedures that would not be required if the equipment was reusable, the people answering the questionnaire felt the procedures would be required in accordance with the following breakdown: 6 would be required every second launch, 0 every third launch, 9 every fourth launch, 6 every fifth launch, and 134 others. Of the 134 other answers, almost all stated that the procedures would be needed "as required" for maintenance purposes.

IF THE EQUIPMENT THAT IS BEING TESTED WAS REUSABLE, (i.e., SPACE SHUTTLE), WOULD THIS TEST BE REQUIRED EACH TIME THE EQUIPMENT IS USED FOR A LAUNCH?

IF NO - HOW OFTEN?

- 1 = Every 2nd Launch
- 1 = Every 3rd Launch
- 3 = Every 4th Launch
- 4 = Every 5th Launch
- 5 = Other - How often?

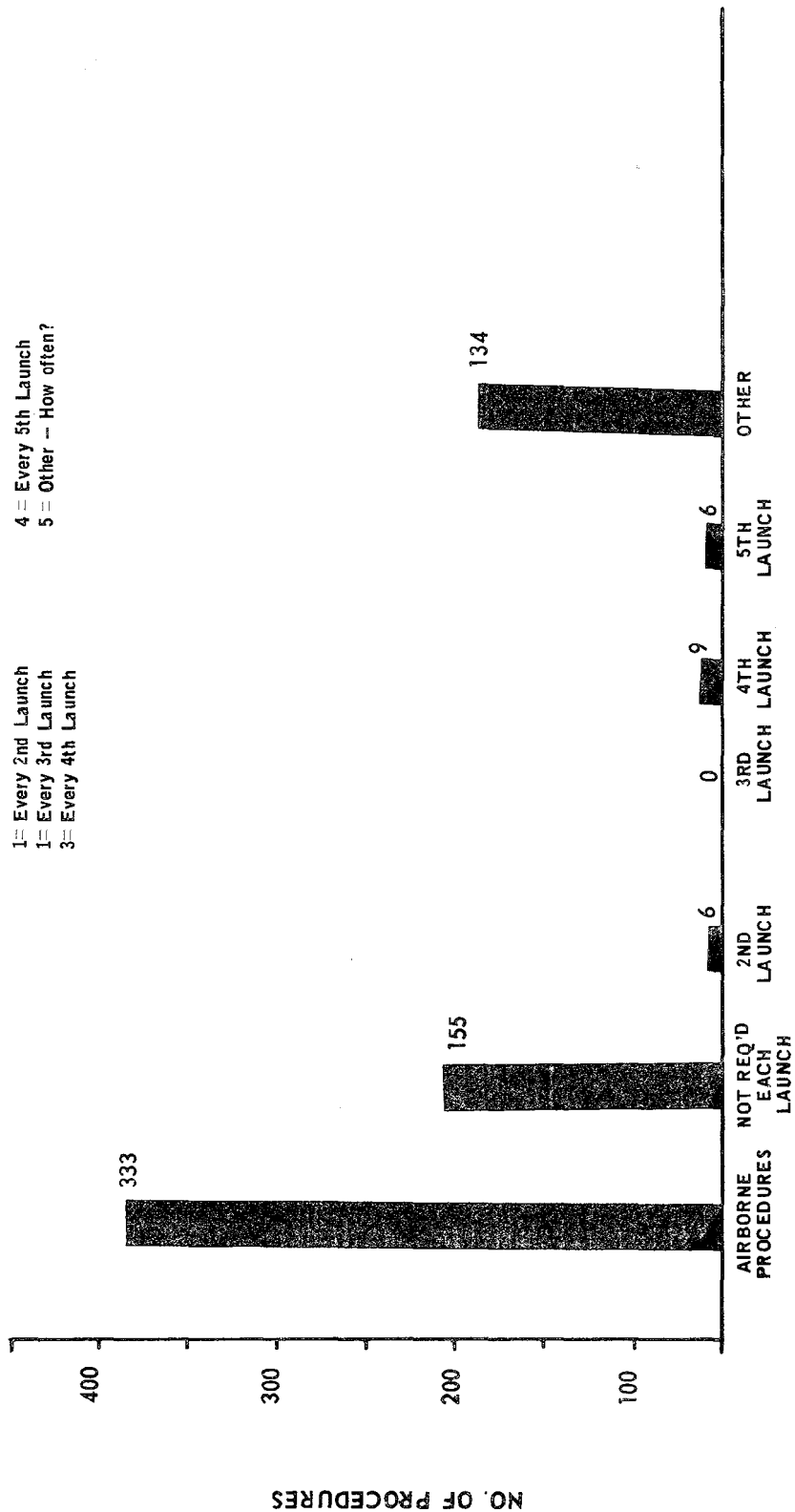


Figure 7

MAJOR TIME CONTRIBUTING FACTOR

The next question, "What is the major time contributing factor in this procedure?" verified what many people already knew. The most significant time contributing factor was the coordination of personnel. See figure 8. Of the total procedure questionnaires received, 278 of the questionnaires answered that this was the major problem. This is due, in my opinion, to three things:

1. The first reason is simple; that is, the many, many people required to operate our Apollo systems. The systems were not designed to keep the number of people to a minimum, but were designed to get the job done in the framework of the Apollo Program and to launch a perfect bird each launch. One specific reason why so many people are required is that they are needed to assess and repair a failed system rapidly so that a given test, or launch, is not delayed or scrubbed. Many of the people would not be required if time was not so important and costly, or if the equipment was designed with economy of personnel as a major driver. On the Shuttle Program, with the automation of testing and the provision of onboard checkout and fault isolation techniques, as well as redundant systems that are being discussed, this problem should be greatly reduced.
2. The second reason personnel coordination is a major problem is due to the geography of a launch complex and the many, spread out and varied operating stations. This fact requires the people involved in testing or checkout to be separated, which in turn requires them to use voice intercom systems and closed circuit TV to conduct the operations. This separation of operating stations invariably causes delays in testing and makes trouble-shooting and associated tasks very difficult and time consuming. On the Shuttle Program, hopefully, operating station and equipment can be arranged so that this problem can be minimized.
3. The third reason for the coordination problem is our Apollo organizational structure.

**WHAT IS THE MAJOR TIME CONTRIBUTING
FACTOR IN THIS PROCEDURE?**

- **COORDINATION OF PERSONNEL**
- **NUMBER OF PEOPLE REQUIRED**
- **GEOGRAPHY**
- **ORGANIZATIONAL STRUCTURE**

Figure 8

NASA-CONTRACTOR ORGANIZATIONAL RELATIONSHIP

As you can see from this chart, see figure 9, there are many "very large" organizations involved in most of the operations and tests performed at KSC, and each of these organizations must manage their own affairs as well as concern themselves with the problems associated with interfacing with and supporting other large organizations. This is not an insurmountable problem as proved by the many successful tests and operations conducted and certainly has been proved workable by the success that has been achieved on the Apollo Program. In many people's opinion this was the only way the Apollo Program could reach its goal. However, for the Shuttle Program, we feel this operational structure can and must be simplified, if we are to have the reduced operation cost that we all know must be achieved if we are to have a successful program.

In addition to the personnel coordination problem, some of the other significant time contributors were:

1. Test preparation
2. Nonoperational hardware design
3. Tight fluid and gas specifications.

NASA - CONTRACTOR ORGANIZATIONAL CHART

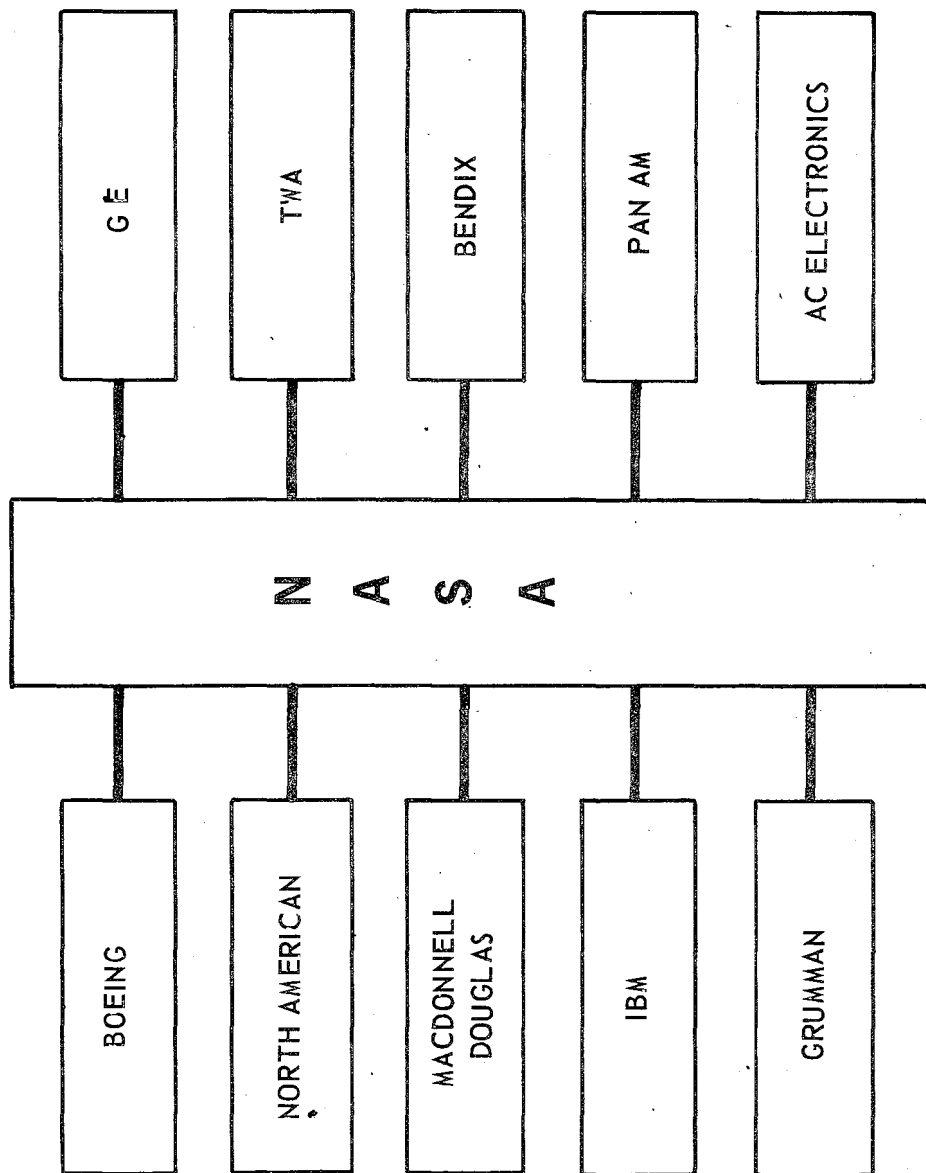


Figure 9

COST SAVING CHANGES

The last question that I would like to discuss from the procedure study is "Are there changes (regardless of cost) that might be made to our operations, ground or flight hardware (including additional instrumentation and automation) that could delete or drastically reduce this procedure?" See figures 10 and 11. Of the 1400 questionnaires, there were 489 procedures that our people felt could be simplified due to hardware changes. The recommended changes ranged from automating the procedure, which would require additional instrumentation in most cases, to deleting hardware and therefore the need for the procedure. Some of the more significant recommendations are shown in the next two figures.

Although I have shown only a few of the many hardware changes suggested, a final report on this study will be available in the near future published by the Center Planning and Future Program Office at KSC that will contain most of the additional recommendations.

- QUESTION 7: ARE THERE CHANGES (REGARDLESS OF COST) THAT MIGHT BE MADE TO OUR OPERATIONS, GROUND OR FLIGHT HARDWARE THAT COULD DELETE OR DRASTICALLY REDUCE THIS PROCEDURE?
- SELF CHECK AND SELF STIMULATION FEATURES SHOULD BE BUILT INTO THE VEHICLE AND GSE TO REDUCE TEST PREPARATION AND TESTING.
- REDUCE THE NUMBER OF INTERFACING LINES (CABLES AND TUBES) TO COMPONENTS AND SYSTEMS.
- MINIMIZE SAMPLING REQUIREMENTS BY ALLOWING WIDER SPECIFICATIONS FOR FLUID AND GASES.
- ELIMINATE UNNECESSARY SYSTEM INVALIDATIONS IN PERFORMING COMPONENT LEAK AND FUNCTIONAL CHECKS.
- ALLOW FOR OVERALL SYSTEM LEAK CHECKS OR PRESSURE DECAY CHECKS RATHER THAN BY LEAK CHECK OF COMPONENTS AND LINES – DEPEND ON FLIGHT DATA TO ESTABLISH LEAKAGE RATE.
- PROVIDE INSTRUMENTATION ON GROUND AND FLIGHT SYSTEMS FOR RAPID LEAK DETECTION.
- MINIMIZE ENVIRONMENTAL EFFECTS TO EQUIPMENT.
- MINIMIZE ENVIRONMENTAL REQUIREMENTS OF EQUIPMENT.
- USE RECHARGEABLE BATTERIES FOR FLIGHT HARDWARE.

Figure 10

- DESIGN THE VEHICLE TO BE HANDLED AND ERECTED WITH QUICK ATTACH FIXTURES.
- DESIGN FOR RISE-OFF DISCONNECTS WHENEVER POSSIBLE.
- MINIMIZE THE NUMBER OF UMBILICALS REQUIRED (PARTICULARLY LIFT-OFF TYPE).
- MAXIMIZE WELDED OR BRAZED CONNECTIONS – USE FLANGE OR B-NUTS ONLY WHERE DISCONNECTION REQUIRED FOR SERVICING AND MAINTENANCE.
- PROVIDE MEANS TO CHECK RELIEF VALVES, CHECK VALVES, AND OTHER MECHANICAL COMPONENTS IN PLACE.
- USE REDUNDANT FILTERS WITH Δ P TRANSDUCERS FOR REMOTE OR AUTOMATIC SWITCHING WHEN REQUIRED.
- ALL INSULATED LINES SHOULD HAVE EASILY ACCESSIBLE AND RAPIDLY REPLACED INSULATION OVER JOINTS.
- ELIMINATE MANUAL OPERATIONS THAT CAN BE AUTOMATED.

Figure 11

TEN MOST TROUBLESOME HARDWARE PROBLEMS ON APOLLO PROGRAM

The next item I would like to discuss with you is shown in figure 12. These ten hardware problems have been determined by the Launch Vehicle and Spacecraft personnel to be the most troublesome problems on the Apollo Program. The thing that makes them so important is that we will face the same problems on the shuttle unless we do something about them; for instance, the first item, valve position microswitches, and the seventh item, transducers. The greatest, most efficient automatic checkout system in the world will depend on items such as feedback switches and transducers to furnish the information it needs to know in order for the system to know what to do when.

34

I would like to discuss briefly each of these items.

TEN MOST TROUBLESOME SPECIFIC HARDWARE PROBLEMS ON APOLLO PROGRAM

- VALVE POSITION MICROSWITCHES
- ELECTRICAL CONNECTORS
- QUICK DISCONNECTS FOR CRYOGENIC AND HYPERGOLIC SYSTEMS
- NON-UNIFORM GROUNDING SYSTEMS
- PNEUMATIC REGULATORS
- CRYOGENIC POINT LEVEL SENSORS
- TRANSDUCERS
- FLIGHT CAUTION & WARNING INDICATORS
- GYROS, PLATFORMS, ACCELEROMETERS & RATE DEVICES
- GROUND/VEHICLE UMBILICALS

Figure 12

1. Valve Position Microswitches:

Extremely high failure rates have occurred on both airborne and ground valve position microswitches. The major reasons are associated with mechanical adjustments and lack of ability of retain settings due to the mechanical nature of the devices and extremely fine accuracies required.

2. Electrical Connectors:

All current electrical connector designs are susceptible to recessed and bent pins with no means to verify satisfactory mate without X-ray; frequent use of dissimilar metals causes galvanic action; for example, patch connectors, printed circuit cards, and standard multiple pin connectors. Frequent failures of solder connections have caused widespread problems in computers, event recorders, voltage monitor cards, and other electrical components.

3. Quick Disconnects for Cryogenic and Hypergolic Systems:

Quick disconnects for cryogenic and hypergolic systems have historically leaked through the flow and poppet seals, giving problems with alignment, in addition to being mechanically difficult to keep clean and serviceable. Reject rate average over 50%.

4. Nonuniform Grounding Systems:

Uncommon and nonuniform grounding system between the flight vehicles hardware/GSE and facility generates noise problems each requiring detailed investigation.

5. Pneumatic Regulators:

Commonplace problems and regulators are seal leakage and drift. Lack of range-ability and precision requires series installations to gain desired output. System complexity and reduced reliability result. High pressure, high flow capacity, and reliability are desirable features that should be improved. Existing designs of all GSE regulators do not lend themselves to automation, requiring either manual or wrench-type adjustments to maintain or change settings.

6. **Cryogenic Point Level Sensors:**
Cryogenic point level sensors do not adequately distinguish between wet and two phase conditions. They cannot be calibrated dry and retain accurate calibration wet thus they are not operationally reliable.
7. **Transducers:**
Pressure and fluid transducers require constant calibration and adjustment and in general have very poor reliability, resulting in changeout at the launch site. Changeout cannot always be accomplished due to lack of accessibility, thus comprising system monitoring.
8. **Flight Caution & Warning Indications:**
Normal cabin switching has created EMI pickup that produces random caution and warning indications and alarms. Each requires investigation and explanation since they could be an indication of impending failure.
Relay switching devices without adequate feedback protection and filtering has required considerable unnecessary troubleshooting to ensure no impending system failures.
9. **Gyros, Platforms, Accelerometers and Rate Devices:**
Most current hardware is not instrumented to allow monitoring of failure trend data, although failure modes are generally known. This often causes late component changeout and increases the amount of subsystem reverification that must often be done at the pad during time critical operations; for example, gyros, motor driven switches, bearings, platforms and hydraulic actuators.
10. **Ground/Vehicle Umbilicals**
Ground/vehicle umbilical assemblies carrying multiple lines and/or electrical disconnects require many manhours to mate, align, leak check, and verify release capability. We need a new approach to produce confidence with minimum expenditures of manhours.

TROUBLESOME APOLLO HARDWARE PROBLEMS CONTINUED

In addition to these ten hardware problems, there is a report coming out very soon entitled "An Analysis of Some Apollo Saturn V Design Features Applicable to the Space Shuttle Which Resulted in Operational Difficulties" that describes many design features that, as the title indicates, caused operational difficulties. Hopefully, we will be able to incorporate into the shuttle design the proper solutions to eliminate these design deficiencies.

APOLLO/SATURN PROCESSING SCHEDULE COMPARISON

The final item to be discussed is the experience we have gained on the Apollo Program in relation to processing times, discrepancy reports, failures, modifications and human factors.

Figure 13 shows the Saturn V vehicle and ground processing time from Apollo 4 through Apollo 14. As you can see, the time decreases down to Apollo 11 and then goes up again. What I would like to discuss at this time is Why!

On the first vehicle, of course, we were using all new people and new equipment; therefore, the time required to process the vehicle was very long--about one year. We used LUT #1 and Pad A. The time required after S-II erection was 260 days.

On the second vehicle, we also were using a new crew, new equipment with the exception of the pad, and the time required to process the vehicle was about the same as the first. We used LUT #2, Firing Room #2 and the same pad as the first, Pad A.

On the third vehicle, Apollo 8, we used the same equipment as was used on the first vehicle and therefore we should have seen a drop in the processing time, but due to the fact that this vehicle was the first manned Saturn V vehicle and the S-II had experienced some flight problems on the previous mission, the S-II stage was removed after being erected for further test to ensure its manned rating. Once the S-II was re-erected, the processing time indeed was much less from this point until launch than the previous two vehicles. Approximately 260 days on the first two vehicles; 152 on the third.

APOLLO/SATURN PROCESSING SCHEDULE COMPARISON

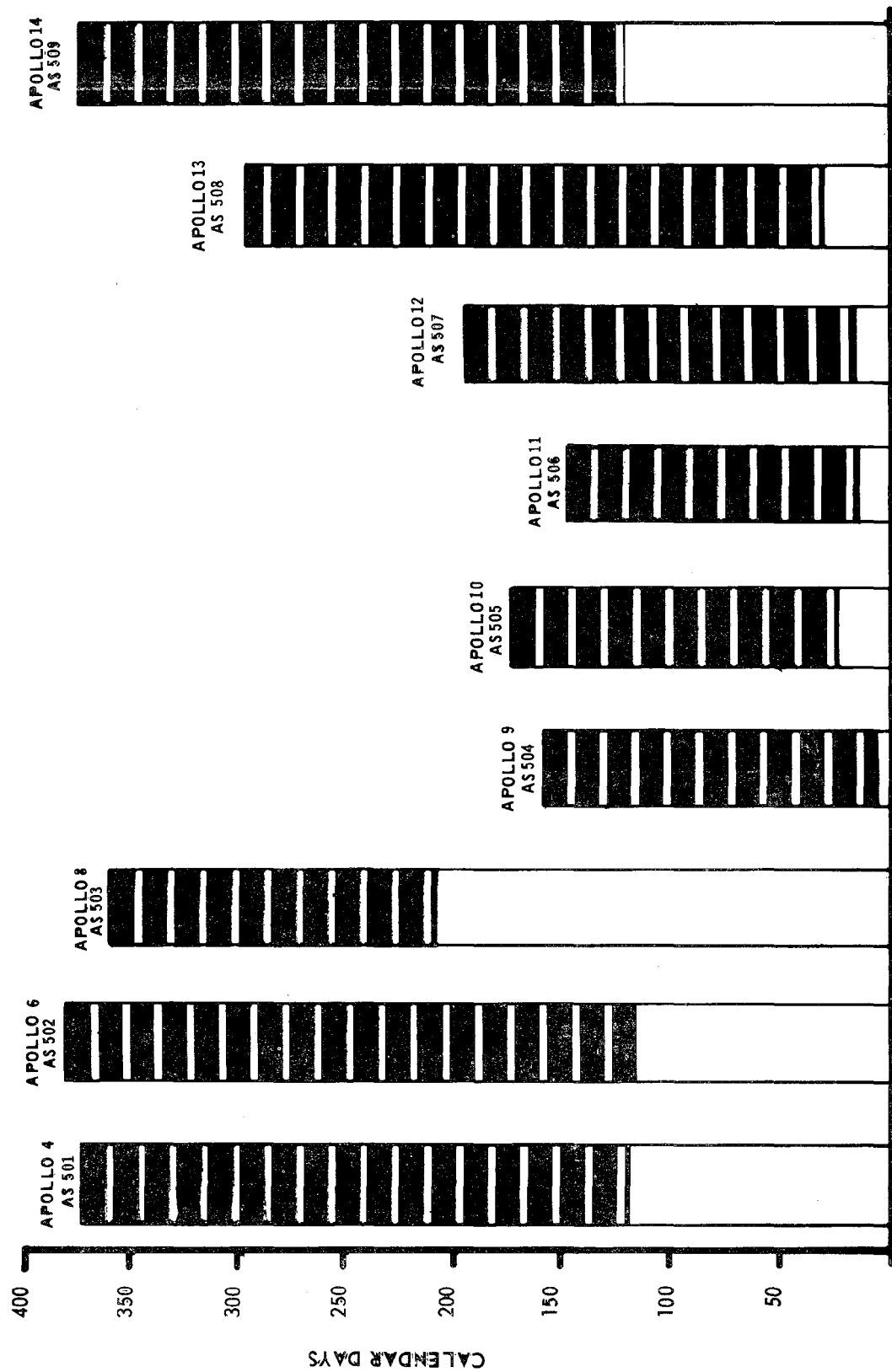


Figure 13

On the fourth vehicle, Apollo 9, we saw a drastic reduction in processing time, but this is misleading because the time from S-II erection until launch was exactly the same as Apollo 8, 152 days. The difference was in the time from S-IC erection until S-II erection. On this vehicle, we used LUT #2, Firing Room #2, and Pad A again.

On the fifth vehicle, Apollo 10, we saw the processing time go up slightly while the time from S-II erection until launch actually went down by nine days. The reason for the total increase in time is that we were using new equipment again. For this launch, we used LUT #3, Firing Room #3 and Pad B for the first time.

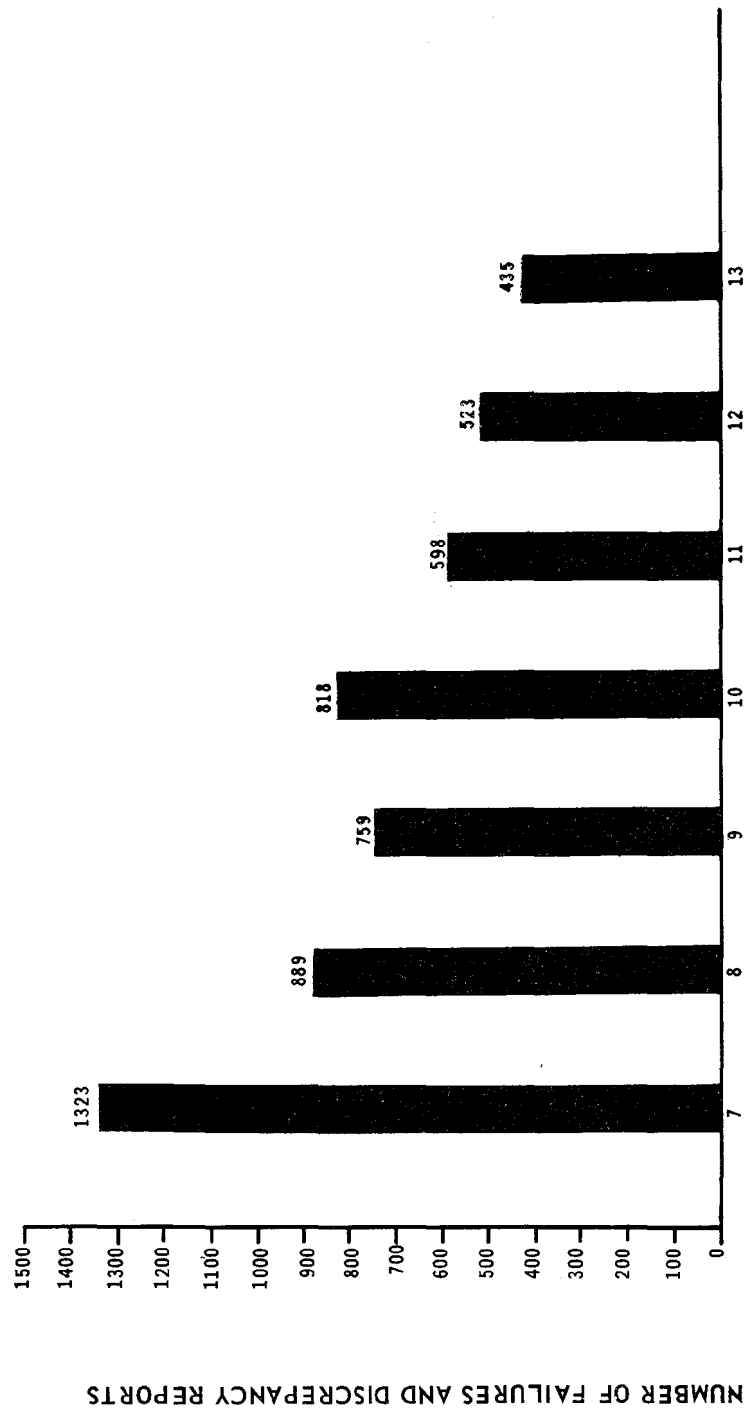
The sixth vehicle, Apollo 11, the vehicle that accomplished the first lunar landing, was processed in the shortest time of any Apollo V vehicle. Once this goal was reached, the launch schedule was relaxed, the personnel reductions began and we saw the processing times lengthen. I don't want to mislead you on this point of personnel reductions, however; we still feel that we can process a vehicle just as fast and probably faster than Apollo 11, but with the current launch schedules, this is not required and therefore all functions are at a reduced pace.

If you will keep this chart in mind, I would like to quickly run through some figures that will show you how some of the other key items that affect Launch Operations looked during these flows and finally how all of this applies to the Shuttle Program.

COMMAND/SERVICE MODULE TOTAL FAILURE REPORTS

Figure 14 shows the total failures that occurred on the command and service module during the processing of Apollo 7 through Apollo 13. As you can see, the number of failures continually decreased with each subsequent launch with the exception of Apollo 10. As explained earlier, this vehicle was launched from a new pad, new LUT and new firing room, in addition to being the first vehicle with a LEM capable of landing on the lunar surface.

COMMAND SERVICE MODULE TOTAL FAILURE REPORTS



APOLLO VEHICLE

Figure 14

LAUNCH VEHICLE HARDWARE TOTAL FAILURE REPORTS

Figure 15 shows the total launch vehicle failures that occurred during the processing of Apollo 4 through Apollo 14. Here again, you can see a continually decreasing number of failures through Apollo 11. After Apollo 11, the number of failures increases slightly; however, I feel this is due to the increased time available for checkout. Had the time available for checkout after Apollo 11 been reduced, I feel that the number of failures would have also continued to be reduced.

LAUNCH VEHICLE HARDWARE TOTAL FAILURE REPORTS

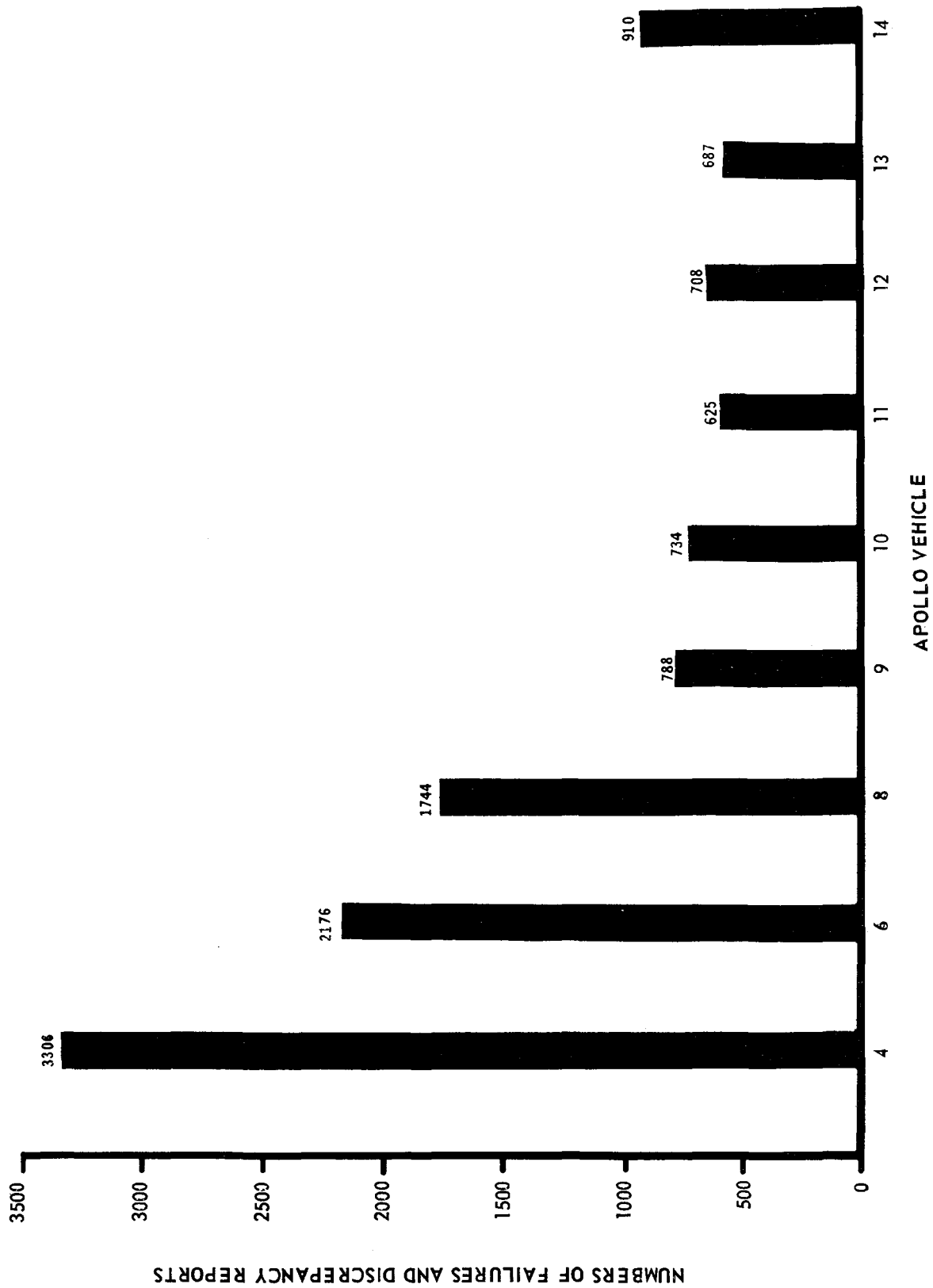
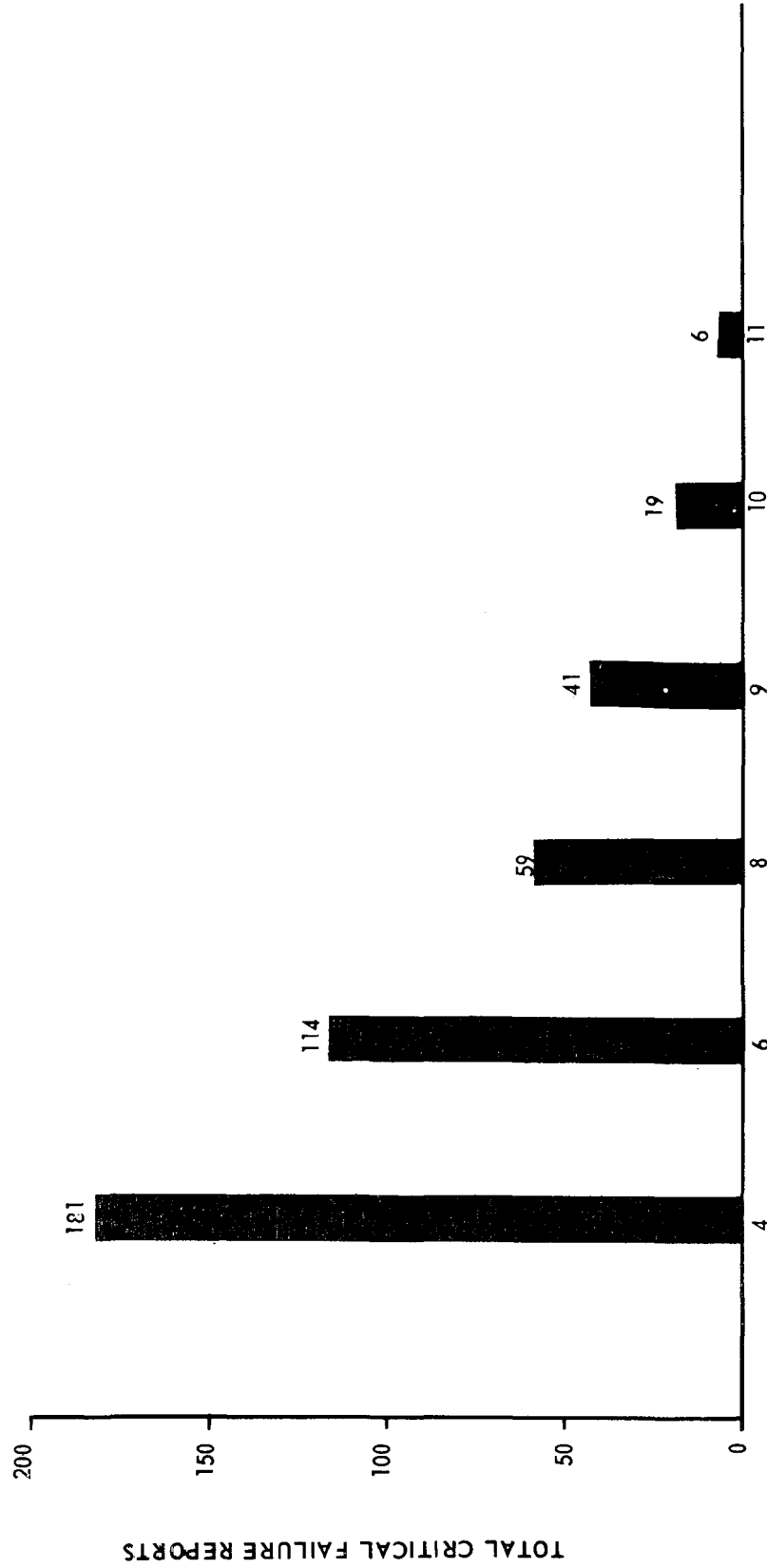


Figure 15

CRITICALITY 01 AND 02 FAILURE REPORTS PER VEHICLE

Figure 16 shows the critical Launch Vehicle failures from Apollo 4 through Apollo 11. Criticality 01 is defined to be a failure that could cause a loss of life or mission. Criticality 02 failure could cause a delay or scrub of a launch attempt. As you can see, just as in the previous figures, the number of critical failures continually decreased with each vehicle.

CRITICALITY 01 & 02 FAILURE REPORTS PER VEHICLE



APOLLO VEHICLE

Figure 16

MODIFICATION MANHOURS USED PER APOLLO MISSION

46 Figure 17 shows the number of manhours used due to modifications from Apollo 8 through Apollo 14. Again, you can see the same trend as seen in previous figures.

LAUNCH VEHICLE AND STAGE FURNISHED GSE MODIFICATION MANHOURS

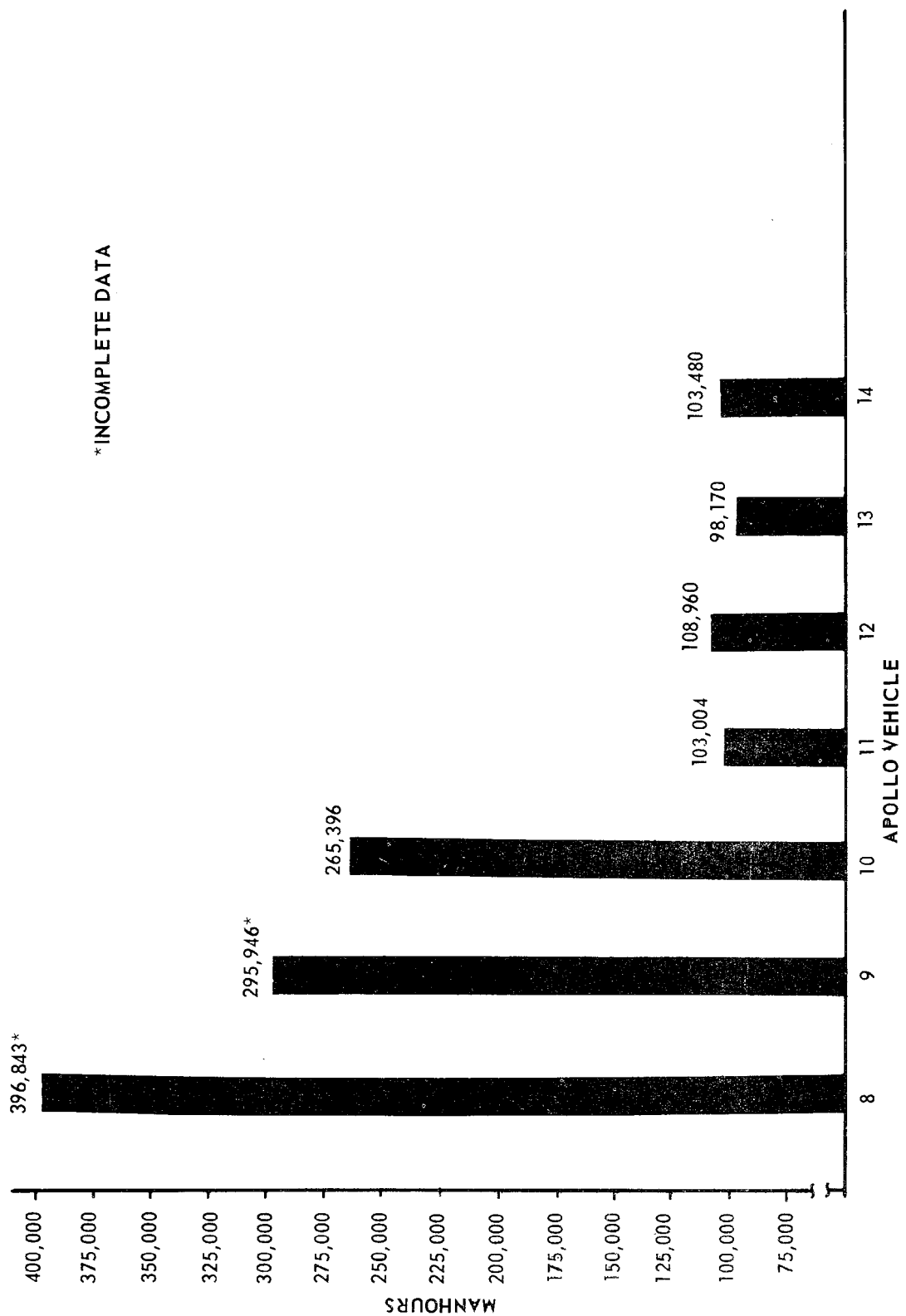


Figure 17

TEST ANOMALIES RESULTING FROM HUMAN FACTORS

Figure 18 shows the number of human errors made during the performance of test on the command and service module and LEM on the Apollo 9 through Apollo 14 vehicles. Again, as on the four previous charts, we see a reduction from vehicle to vehicle. I believe we have seen a reduction in human errors due to experience or learning curve as well as improved procedures.

TEST ANOMALIES RESULTING FROM HUMAN FACTORS CSM-LM

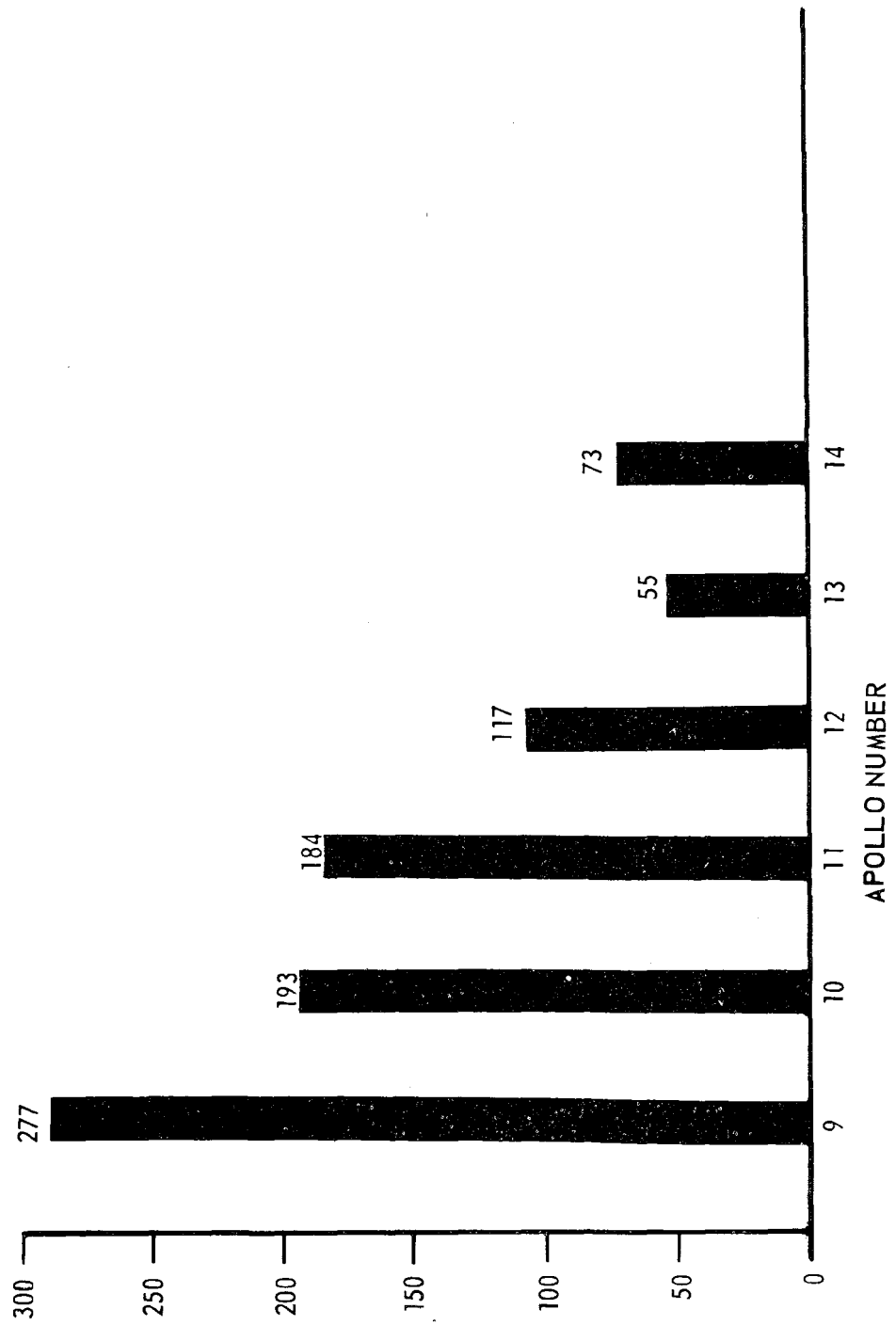


Figure 18

LAUNCH SCHEDULING

Finally, figure 19 shows what we call our shuttle launch capability curve. We feel that with a vehicle delivery rate of one orbiter and one booster from manufacturing every six months, and with a fleet size of four boosters and five orbiters, that within two years and approximately 25 flights we can reach our goal of a two-week turnaround. The curve is based on the assumption that most of the problems previously discussed can and will be solved and that we, the aerospace industry, will take advantage of the experience gained on the Apollo Program.

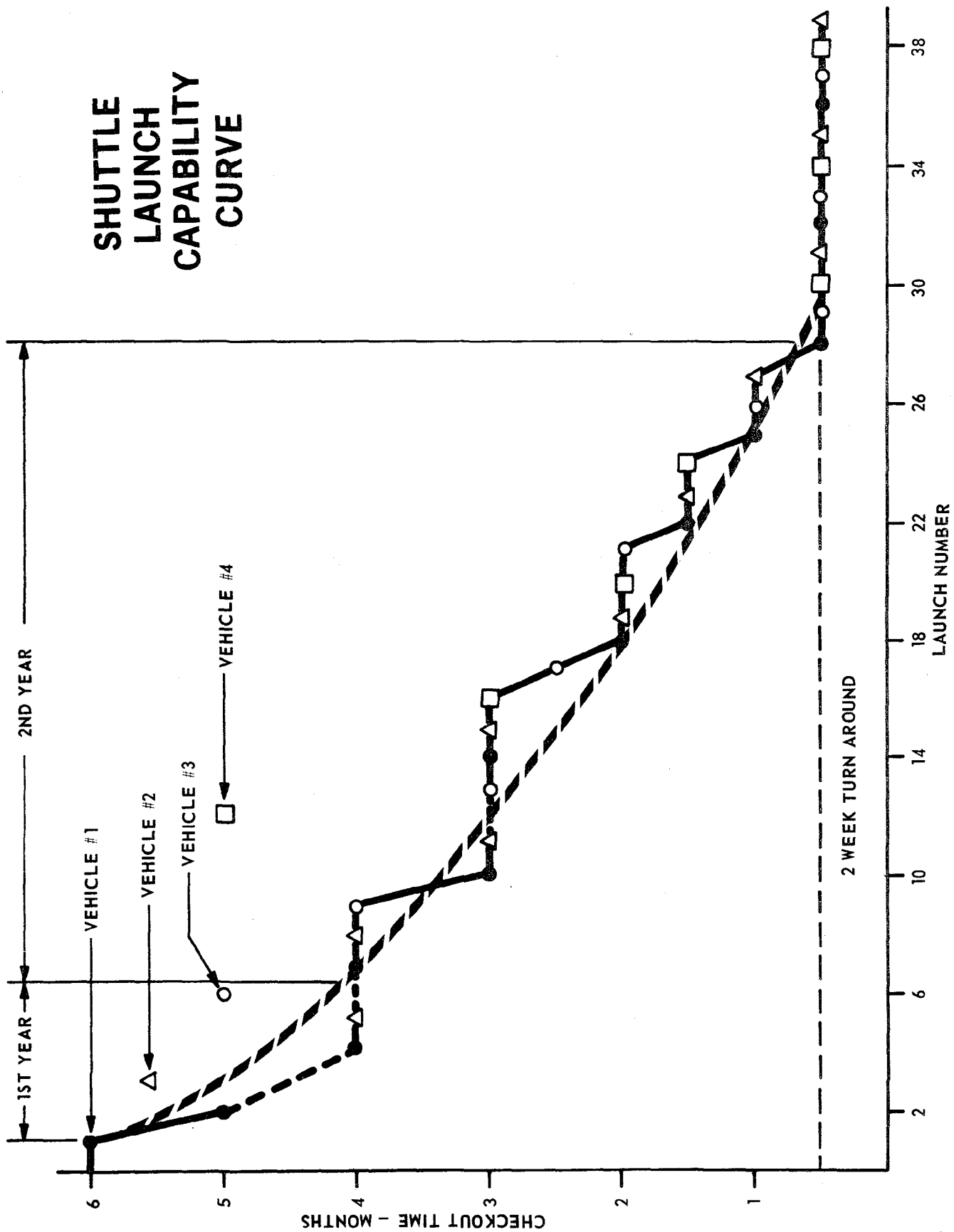


Figure 19

WATERFALL PROCESSING OPERATIONS

This waterfall processing chart, figure 20, shows what we feel the major operations will be when the shuttle is fully operational and we have reached our goal of a two-week turnaround. This figure will be updated and revised as new and more refined information becomes available during the design of the shuttle hardware.

INVESTING IN THE PLAN

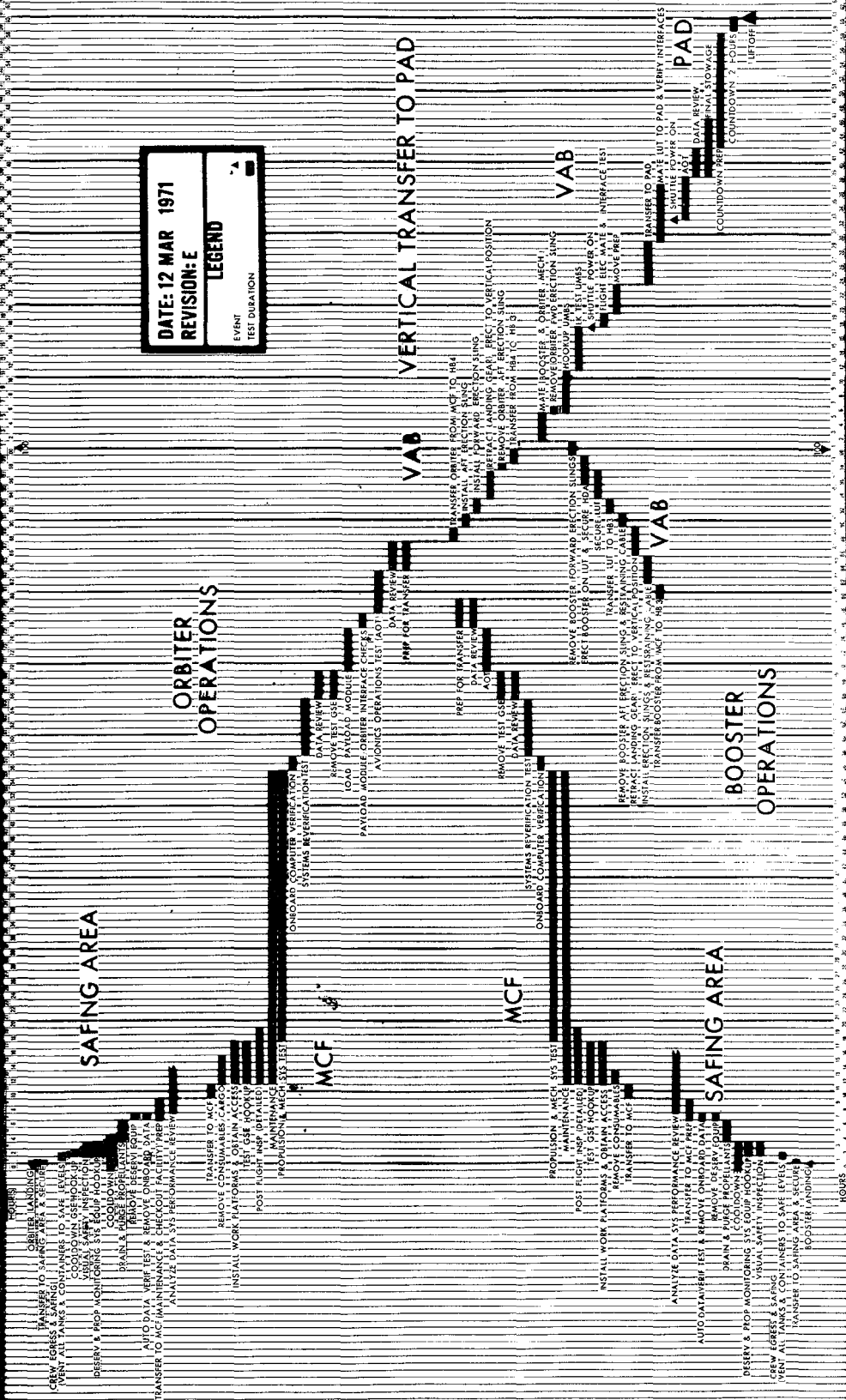


Figure 20

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AIRLINE VIEWPOINT OF SPACE SHUTTLE MAINTENANCE CONCEPTS

Nicholas Krull

American Airlines

INTRODUCTION

My purpose today is to identify commercial airline maintenance concepts which offer the promise of minimizing Space Shuttle maintenance costs. Airlines are uniquely qualified to offer judgements in this field due to the perishable nature of our product: Namely, available ton miles. Airline management decisions continually involve an economic tradeoff between: The quality of service provided ... such as safety, convenience, comfort, and on-time departures; and the cost of maintaining the desired quality of service. The final test of operational profitability comes down to our ability to minimize and control the maintenance costs required to sustain the desired level of service.

It is therefore necessary for me to first review the latest and most significant elements of "The Airline Maintenance Philosophy." I will put special emphasis on the unique management support systems in current use at American Airlines. I will then proceed to illustrate where this philosophy can be applied to Space Shuttle maintenance requirements as they are currently envisioned. I will conclude with some judgements about major differences between an airline maintenance environment, and operational conditions unique to the Space Shuttle.

AIRLINE MAINTENANCE COSTS

Airline maintenance costs have increased to a disproportionately large percentage of "total" aircraft cost in recent years. In a 15-year aircraft life cycle, these costs amount to approximately three times the original aircraft purchase price. For some aircraft components and systems, this relation between maintenance cost and purchase price exceeds a 3:1 ratio by a wide margin. See Figure 1.

A variety of airline management control indices are used to monitor and control the maintenance operation. The cost per available ton mile parameter provides a measure of cost in relation to the amount of payload available. The operating hour data indicates the cost level in relation to the mission activity level. The cost per maintenance visit reflects the cost per unit of maintenance base activity. These basic measures are used by most airlines and all three are required to perform the maintenance management function.

Budget control information is provided on a monthly basis and includes actual maintenance cost compared to forecast maintenance cost. These are reviewed on a monthly basis and corrective action programs are initiated when cost overruns occur. See Figure 2.

Airline Maintenance Costs

- **2½-3 TIMES COST OF PURCHASE PRICE OVER LIFE OF VEHICLE**
- **MANAGEMENT CONTROL INDICES**
 - **COST PER AVAILABLE TON MILE**
 - **COST PER OPERATING HOUR**
 - **COST PER MAINTENANCE VISIT**
- **BUDGET CONTROLS**
 - **MONTHLY COMPARISONS OF MAINTENANCE COSTS**

Figure 1



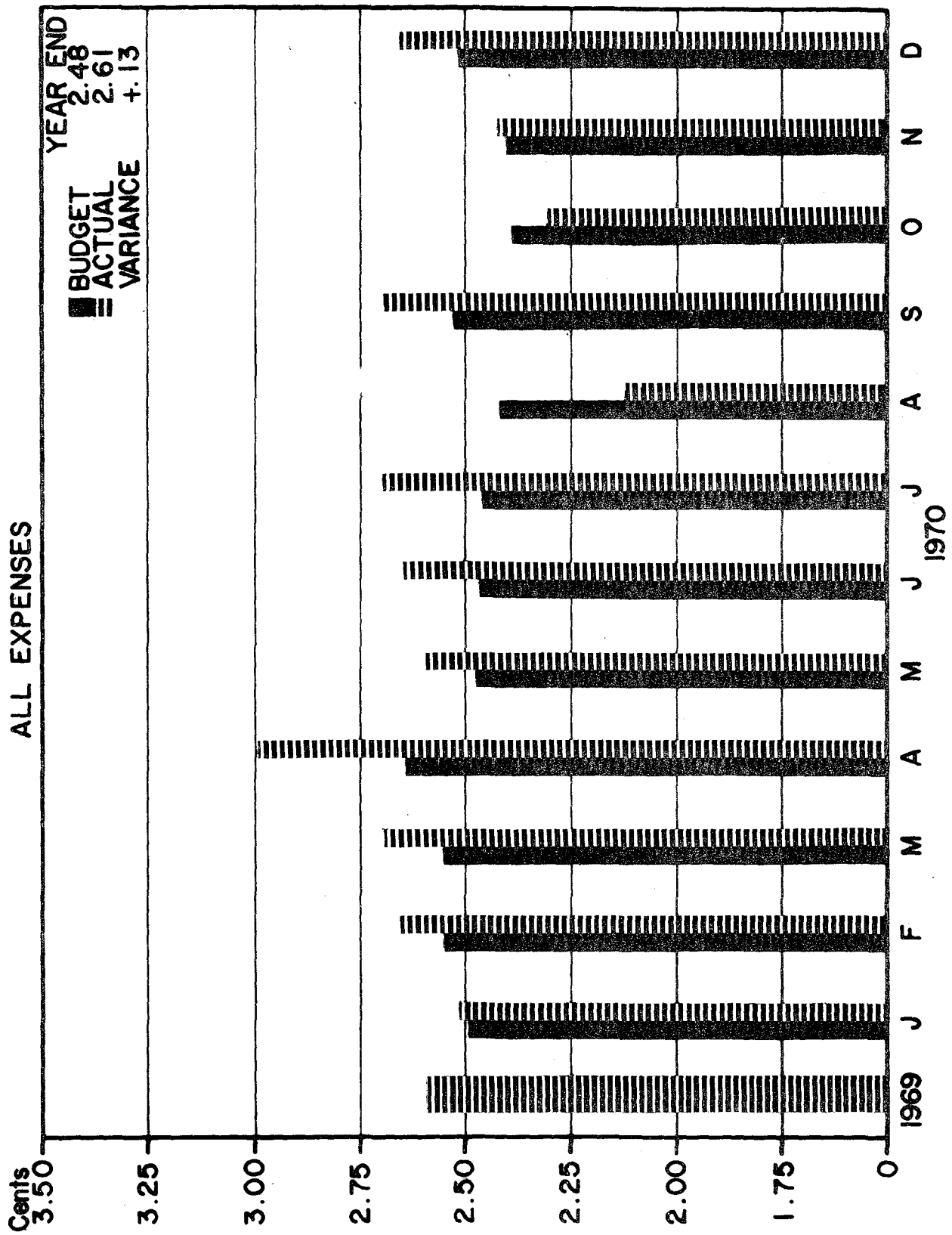


Figure 2

MAINTENANCE CONCEPTS

Scheduled maintenance in the airline industry today consists of a composite of cleaning services, inspection, functional test, adjustment, removal, replacement, and reconditioning work performed at rigidly controlled time intervals. As experience is acquired, or as conditions change, these elements of the scheduled maintenance program are revised upward or downward in terms of the original time intervals. Underlying this is an extensive system of data collection, communication, analysis, and planning. See Figure 3.

Unscheduled maintenance consists of on-aircraft and off-aircraft troubleshooting, fault isolation, repair, and replacement of components resulting from the indicated defect or malfunction.

Airline on-aircraft maintenance concepts revolve around a practical tradeoff between aircraft availability, elapsed time, and maintenance man-hour requirements. Airlines are very sensitive to aircraft downtime and the resultant high cost impact. Each hour of downtime for component replacement is worth \$90 in interest, alone, on a four-engine jet. For the 747 jumbo jet it is approximately \$175/hour. These economics require that we minimize aircraft out-of-service time for maintenance causes.

The maintenance philosophy for determining where to perform the off-aircraft maintenance, either on-site or off-site, is another economic tradeoff, with the parameter of spares cost added.

CONCEPT DEVELOPMENT

Airline maintenance programs were once based almost entirely on the time limit concept. See Figure 4. This scheduled maintenance concept required almost all component replacement and other maintenance action to be performed at fixed time intervals. This concept was based on the following beliefs:

1. Wearout is a common defect and is a function of time.
2. Inspections at fixed time intervals can detect failures.
3. Overhauls at fixed time intervals can prevent failures.

In the early days of air transportation, these concepts were realistic since the designs were relatively simple and equipment could be easily and quickly inspected. Such inspections were also quite effective in detecting potential failure modes. For the same reasons, overhaul was relatively easy to accomplish. These early maintenance concepts led to rigidly defined inspection and overhaul periods, commonly known as time between overhaul or TBO intervals.

Since 1948, air transport designs have become significantly more complex due to improvements and advances in safety, performance, efficiency, and comfort. This technological trend has created a need for the development of new and revised maintenance

Maintenance Concepts

- **SCHEDULED MAINTENANCE**
- **UNSCHEDULED MAINTENANCE**
- **ON-AIRCRAFT**
- **OFF-AIRCRAFT-ON SITE**
- **OFF-AIRCRAFT-OFF SITE**

Figure 3

CONCEPT DEVELOPMENT

- PREVIOUS FIXED TIME CONTROL CONCEPT
- MIGRATION TO ON-CONDITION
- SIMPLE vs. COMPLEX FAILURES
- DEVELOPMENT OF CONDITION MONITORED MAINTENANCE-ENGINES
- DEVELOPMENT OF CONDITION MONITORED-AIRFRAMES
- FAA PHILOSOPHY

Figure 4

concepts. See Figure 5. The airlines have shown that complex units do not follow the same failure pattern as simple parts. A great majority of components do not have an increasing failure rate with time in service. This characteristic has been confirmed through the experience of many airlines in recent years. This background, in turn, has led to the development and acceptance of many new Condition Monitored Maintenance (CMM) concepts and programs. The Federal Aviation Administration has also played an active role in the development and implementation of these new airline maintenance programs. Without their complete cooperation and approval the major changes in airline maintenance concepts which have taken place in the last five years would not have been possible.

AMERICAN AIRLINES' RECONNAISSANCE

This program is a system that integrates the efforts of Flight, Overhaul, Line Maintenance, Engineering, Production Control, Inspection, and Supply in the detection, identification, and solution of technical problems. This is accomplished through a data collection and analysis system which assists a Problem Action Board in determining the necessary corrective action programs.

CONDITION MONITORED MAINTENANCE

This is American Airlines' maintenance program for turbine engines which combines management systems and computer techniques to determine the necessary corrective action to continue the engine in service. Some of the major benefits of this program are: Improved schedule reliability, improved maintenance practices, and concentration of engine inspections to the specific needs of the engine.

FIELD MAINTENANCE RELIABILITY

This is a computer system that is a part of our nation-wide reservation system for keeping track of the maintenance status and needs of each airplane in the fleet. Maintenance actions and requirements are available to any city where a particular aircraft stops. This is used to determine the next appropriate maintenance action.

COMPONENT RELIABILITY ANALYSIS METHOD

Figure 6 is the result of our analysis of component age-failure techniques using this system. It consists of a computer program utilizing actual techniques to analyze the failure rates as the components get older in their life cycle. The computer analysis is provided the engineer and he uses this as a tool to determine what adjustments in the maintenance program might be required.

COMPARISON WITH 747 OPERATION

Figure 7 depicts major similarities and differences which indicate that some of the Boeing 747 maintenance program concepts can be applied directly to Space Shuttle vehicle maintenance.

MAINTENANCE PROCESSES MIGRATION

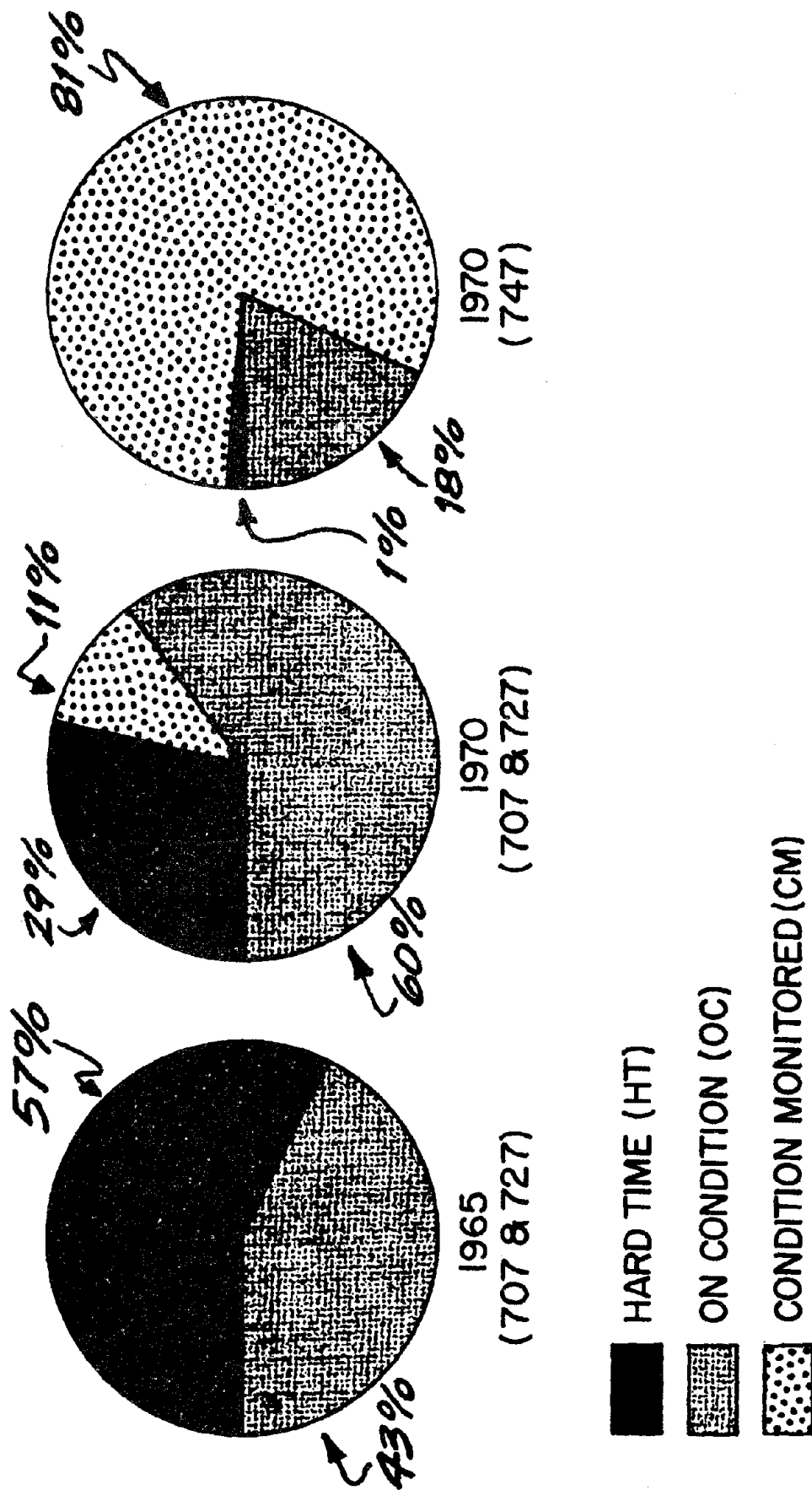


Figure 5

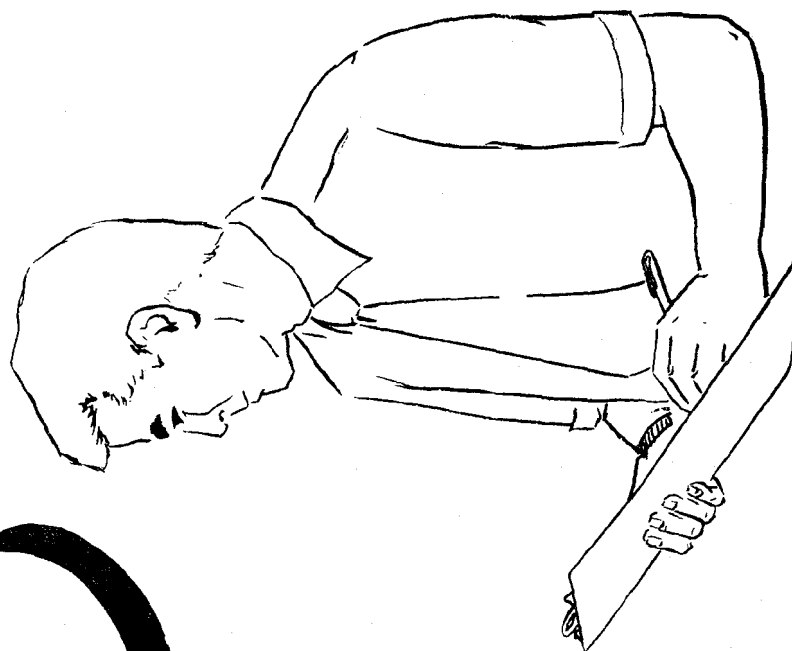
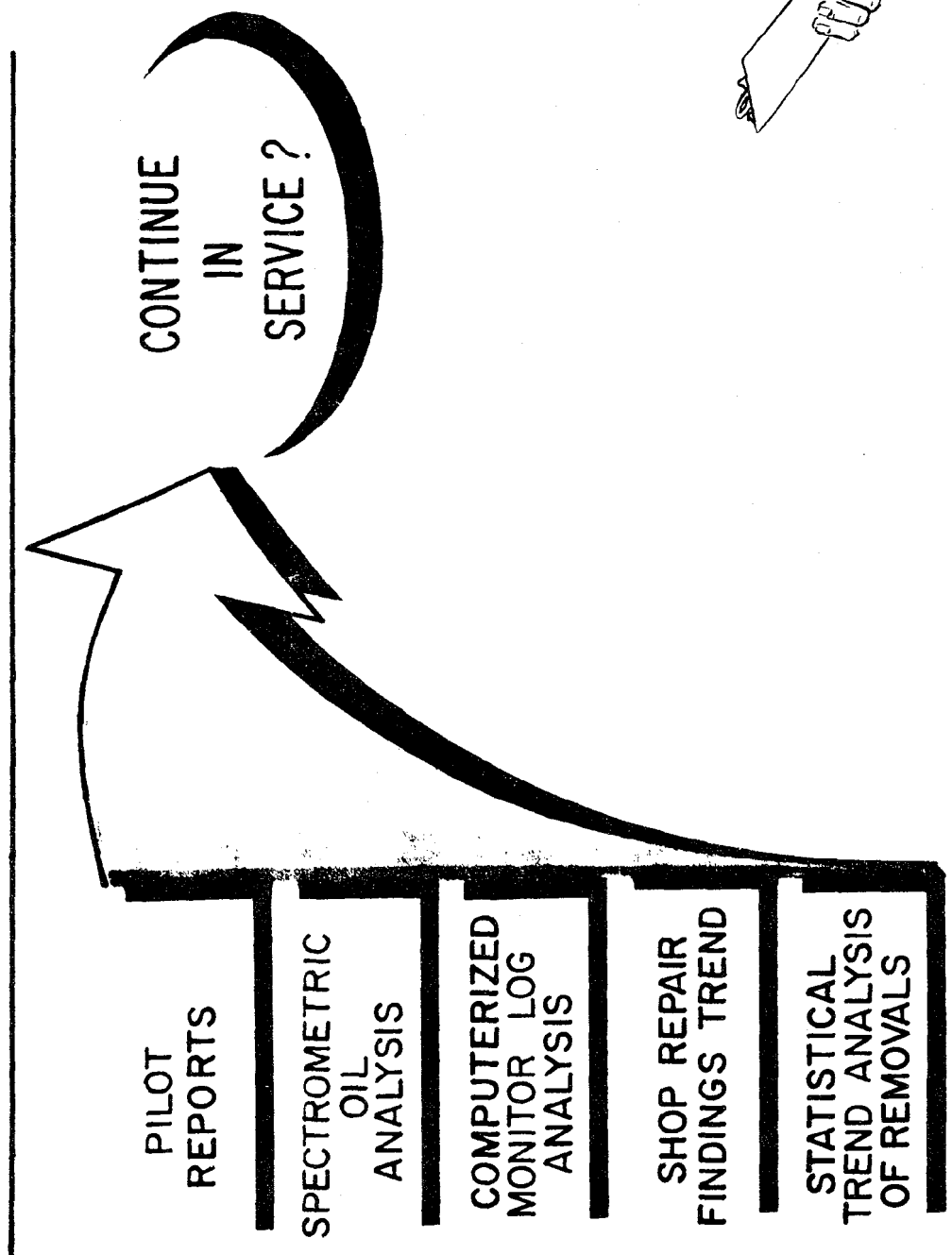


Figure 6

Shuttle Maintenance Concepts Comparison With 747 Operation

<u>SHUTTLE</u>	<u>747 AIRCRAFT</u>
A. SINGLE OPERATING BASE	A. SINGLE MAINTENANCE BASE
B. FEW ACFT (5 TO 3)	B. FEW ACFT (16)
C. SIMILAR DOCKING REQMTS.	C. SIMILAR DOCKING REQMTS.
D. HIGH COST OUT OF SERVICE	D. HIGH COST OUT OF SERVICE
E. FEW FATIGUE CYCLES	E. MANY FATIGUE CYCLES
F. SEVERE VIBRATIONS	F. NEGLIGIBLE VIBRATION
G. SEVERE TEMP. CYCLING	G. NEGLIGIBLE TEMP. CYCLING
H. LOW ABES HEAT CYCLES	H. LOW ABES HEAT CYCLES
I. SINGLE BASE SPARE REQ'S	I. MULTI-BASE SPARES REQ'S
∴ 747 TYPE MTNC. PROGRAM FOR SHUTTLE	

Figure 7

PRIOR TO EARTH LANDING

The accumulation and diagnosis of telemetered mission data will be required as a complement or substitute for many post-mission functional tests on the Space Shuttle vehicles. See Figure 8.

1. Due to inability and/or cost of simulating a space environment after earth landing.
2. Because a 14-day maintenance turnaround interval does not permit time to conduct elaborate and extensive ground tests.

This data will be used to establish the unscheduled maintenance bill of work to be accomplished after return of the mission vehicles to the maintenance base site. This characteristic of the Space Shuttle operation is analogous to the airline which employs a Condition Monitored Maintenance (CMM), or on-condition, maintenance philosophy to minimize out of service time due to maintenance.

SAFING AND RETRIEVAL AFTER EARTH LANDING

After the separate earth landings of the orbiter vehicle and the booster vehicle, a retrieval crew will be required to perform the safing operation, which includes the purging of unused cryogenics such as liquid oxygen and liquid hydrogen. Following the safing operation, the retrieval crew will assist in the egress of the flight crew, remove the mission cargo (which may require precautions against radioactive contamination), and remove the on-board data recording devices. In the event the initial earth landing is made at the destination maintenance base site, the Space Shuttle vehicle will have to be towed to the maintenance facility for the start of turnaround maintenance action. See Figure 9.

Alternatively, the vehicles will have to be prepared for ferry flight return to the maintenance base site, if an off-site landing was initially required. As currently defined, this ferry flight preparation will include strapping on air breathing engines, fueling, general servicing, and the necessary air traffic control clearances.

Here, again, we find Space Shuttle requirements which are analogous to the typical airline operation. Airline expertise in these areas can be an extremely valuable input to the operational planning for Space Shuttle vehicles.

SCHEDULED MAINTENANCE, ETC.

The desire will be to minimize scheduled maintenance requirements after vehicle return to the maintenance base site. Nevertheless the eventual maintenance program for the Space Shuttle vehicles will require some degree of scheduled maintenance in accordance with fixed times between repair and overhaul. See Figure 10.

Maintenance Flow

- **PRIOR TO EARTH LANDING**
 - **DATA TELEMETRY**
 - **FAULT DIAGNOSIS**
 - **MAINTENANCE PLANNING**

Figure 8

Maintenance Flow (cont'd)

SAFING & RETRIEVAL AFTER EARTH LANDING

- PURGING**
- POTENTIALLY RADIO ACTIVE CARGO REMOVAL**
- OTHER FLUSHING & DECONTAMINATION**
- MOVE OR FERRY TO MAINTENANCE SITE**

Figure 9

Maintenance Flow (cont'd)

- **SCHEDULED MAINTENANCE**
 - **REPLACE VS. REPAIR**
 - **DEFERRED MNTC / MEL POLICY**
 - **FIXED TIME VS. ON-CONDITION**
 - **CONFIGURATION CONTROL**

- **INVENTORY & LOGISTICS**
 - **SPARE COMPONENTS**
 - **SPARE MATERIAL**

Figure 10

A deferred maintenance program will need to be developed to identify non-critical items that can be deferred or rescheduled to a subsequent turnaround check. These items could be controlled by what is known in the airlines as a Minimum Equipment List (MEL). MEL specifies allowable tolerances for deactivated components and systems, and the checks required to assure backup system integrity.

Some of the criteria used by the airlines to choose between scheduled maintenance and on-condition maintenance are directly applicable to the Space Shuttle. Criteria similar to the ones used during development of the 747 maintenance program should be considered. Airline configuration control programs are also applicable to a comprehensive Space Shuttle maintenance program.

Airline inventory and logistics concepts are applicable to the Shuttle Program. Computer models to determine spare component and material levels are adaptable and could contribute significantly to the optimization of inventory investment levels.

UNSCHEDULED MAINTENANCE, ETC.

Many of the Condition Monitored Maintenance concepts employed by major airlines can be applied directly to Space Shuttle vehicles. It is highly desirable that most maintenance activities be performed after it is determined that an "out-of-tolerance" condition exists. Preventive maintenance should be limited to those cases where unscheduled maintenance is required or reliability can be improved.

Implementation of an on-condition maintenance concept requires the maximum use of all available data from the mission, post-flight inspections, and post-flight tests in order to establish the need for corrective maintenance action. The capacity to implement on-condition concepts is highly dependent on the application of such maintainability design concepts as: On-aircraft accessibility; the ease of fault isolation; the predictability of failure modes; and the ease of required remove and replace tasks. See Figure 11.

The airlines are uniquely experienced in these maintenance disciplines. There is a constant pressure on airlines to minimize out-of-service time for maintenance, to assure on-time departures and to minimize total operating costs, all at the same time. Again, airline experience with these operational constraints is directly applicable to the constraints of a Space Shuttle operation.

QUALITY ASSURANCE, ETC.

The quality assurance approach to Space Shuttle vehicle maintenance is a key element in realization of the 14-day turnaround goal. The following comments relate to maintenance base inspection requirements during turnaround only:

A variety of test and inspection techniques need to be utilized to optimize cost effectiveness, such as nondestructive, self test and automatic test techniques. It is

Maintenance Flow (cont'd)

- **UNSCHEDULED MNTC.**
 - **SOURCES:**
 - Telemetered data
 - Crew debrief
 - Onboard recording
 - Post flight checkout
 - Inspection & test
 - **IMPORTANCE OF:**
 - Accessibility
 - Fault isolation
 - Predictability
 - Removability
 - Replacibility

Figure 11

envisioned that diagnostic analyses will need to be performed by computer during the checkout cycle to isolate the cause of malfunction and to determine the repair/replacement necessary to return such hardware to an acceptable condition. Verification and acceptance criteria should be studied from an airline operations standpoint to determine their application to Space Shuttle vehicles. Airline traceability and documentation methods should also be studied as a means of achieving the 14-day turnaround goal. See Figure 12.

The following airline maintenance support concepts appear to be directly applicable to the Space Shuttle at this time:

1. The airlines use a number of computer programs to analyze and diagnose the condition of the aircraft and determine maintenance requirements. Some of these are: Computerized Engine Monitor Log, Eppi oil analysis, oil consumption data, Airborne Integrated Data System.
2. Inventory models are used to optimize spare allocations and minimize inventory levels. They also assist in the repair versus throw-away decisions.
3. The techniques used to develop ground support equipment and tooling requirements and procedures for airline turnaround maintenance appear to have application to the Space Shuttle.
4. Certain airline concepts of personnel selection and training can be applied, including skills, aptitudes and certification requirements unique to Space Shuttle technology.

CONCLUSIONS

From the foregoing discussion of airline maintenance concepts and their applicability to the Space Shuttle Program, we can conclude that many of these concepts can be directly applied. We must, however, at the same time recognize limitations to the direct application of these concepts.

In its early operation the Space Shuttle will not have the benefit of more than 1,300 takeoffs and landings each day to develop empirical experience. The maintenance program will have to depend much more heavily on information developed by the designer.

The vehicles will indeed have redundancy in their systems but not to the extent of a modern airline passenger aircraft. The maintenance program must recognize this lower degree of redundancy.

Perhaps the greatest limitation will be the psychological and to some degree, very real concern over the consequences of a single failure. Commercial aircraft have an exceptionally high tolerance to failure and although not common, have the capability to

Maintenance Flow (cont'd)

- **QUALITY ASSURANCE**
 - **TESTING**
 - **Checkout**
 - **Verification**
 - **Acceptance**
 - **TRACEABILITY**
 - **DOCUMENTATION**

- **APPLICABLE SUPPORT CAPABILITIES**
 - **COMPUTERIZED DIAGNOSIS**
 - **INVENTORY MODELS**
 - **GROUND SUPPORT REQ'MTS**
 - **TOOLS & EQUIPMENT**
 - **PERSONNEL-SELECTION & TRAINING REQ'MTS**

Figure 12

make unscheduled landings at alternate airports. There will be a far greater concern for the consequences of a failure on the Space Shuttle and this, to a large degree, will be directly related to the environment or mission envelope within which it operates. Recognizing these limitations and building them into the maintenance planning, we can readily see that Condition Monitored Maintenance can be applied to the Space Shuttle. We believe that it will be necessary in order to achieve the projected 14-day turnaround and the desired low cost operation of these vehicles. In addition to the maintenance concept many of the management systems can be modified to recognize and control operating costs while at the same time improving the dependability for assuring on time departures. See Figure 13. I cannot stress too highly that not only the similarities but the differences must be recognized and built into the maintenance plan at the time of design if we are to expect the desired maintainability in the operation of the Space Shuttle Program.

Conclusions

LIMITATIONS

- **EMPIRICAL EXPERIENCE**
- **REDUNDANCY**
- **FAILURE CONSEQUENCE**

APPLICABLE AIRLINE CONCEPTS TO BE APPLIED

- **CONDITION MONITORED MAINTENANCE NEEDED TO ACHIEVE 14 DAY TURNAROUND.**
- **AIRLINE APPROACH TO ACHIEVEMENT OF A LOW COST OPERATION.**
- **MAINTENANCE MANAGEMENT SYSTEMS FOR MINIMIZING OPERATING COSTS.**
- **MANAGEMENT SYSTEMS TO ASSURE ON-TIME DEPARTURES.**

Figure 13

W71-36196

ONBOARD VERSUS GROUND CHECKOUT OF FLUID MECHANICAL SYSTEMS

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ABSTRACT

The low cost and quick turnaround requirements of the Space Shuttle Program suggest an investigation of the economics of automated checkout systems. This paper discusses the trade-off of autonomous onboard checkout versus ground checkout of the Space Shuttle Systems. Evaluation is made of the feasibility of automatic servicing, checkout, trend analysis, and fault isolation of fluid mechanical systems. Computer controlled checkout techniques including Shuttle to GSE electrical interfaces are examined. New concepts of testing are discussed and compared to previous methods of automated checkout, the ultimate objective being an optimum Space Shuttle checkout philosophy.

INTRODUCTION

The one objective of the Space Shuttle program having the most dramatic impact on the ground checkout philosophy is quick turnaround. The basic turnaround time frame is from landing through deservicing, ground maintenance and checkout, propellant and cargo loading, and finally to liftoff. The total lapsed ground time: 14 days.

For quick turnaround, an automated checkout method must be utilized in ground checkout of the complex onboard systems. This method must be more than the typical go/no-go type of analysis. It must automatically determine vehicle system health, trend analysis, and fault isolation down to the Line Replaceable Unit (LRU). A determination of whether the automated checkout system should be onboard the vehicle or on the ground must be made.

The degree of autonomy for any space vehicle is a function of its capability for self-test. Automatic test capabilities must be incorporated into the vehicle system at the onset. The basic design of each component and subsystem should lend itself to onboard test, fault isolation, and trend analysis. If a system is designed for its operational requirements only, with test capabilities implemented as an after thought, the design becomes complex, overweight, troublesome, and in many instances unreliable. Ground checkout can be divided into the various areas of mechanical, electrical, and fluid mechanical. We will examine some of the work accomplished to date in automatic ground checkout, and then address the little known area of automatic fluid mechanical checkout, as applicable to Space Shuttle and other space vehicles of the next generation.

AUTOMATIC CHECKOUT TECHNIQUES

A brief look at past vehicle checkout systems and at a system proposed for Shuttle is required to define the checkout configuration that will be available for use on fluid mechanical systems of the future.

At Kennedy Spacecraft Center, an automated checkout system is used for high bay prelaunch and pad testing of the Saturn V launch vehicle.¹ In the last 20 hours of countdown, the checkout system provides an automated capability for 85% of the required functions.

A computer and associated equipment required to service and checkout the Saturn V are located in the Mobile Launcher. A similar computer plus test consoles are used in the Launch Control Center (LCC) to monitor and control the Saturn V operations. The computers communicate via a data link.

Data from the Saturn V Launch Vehicle and the support equipment is gathered by the checkout system through telemetry and hardware interfaces. The checkout system monitors the status of over 5000 discrete events.

Another example of an existing automated checkout system is the factory and static test facility used to completely test the Saturn IVB stage during factory test and to control and monitor the static firing program at the Sacramento test facility.

The SIVB checkout system contains about 30 units of equipment including a computer with its peripheral hardware, a computer interface unit, and operator test stations. The system provides automatic event sequencing, monitors 1520 bilevel and 127 analog signals, and also uses the computer to interpret test results. The checkout system interfaces with the SIVB via many hardwires as well as a telemetry system.

A third computerized system is Acceptance Checkout Equipment (ACE)¹ used to checkout the Apollo spacecraft. The Command Service Module of the Apollo is checked out by an ACE station containing 25 high and 27 low consoles, 1416 event lights, 216 meters, 160 channels of analog recording, 516 channels of event recording, and 19 cathode ray tube displays. A similar ACE station is used for Lunar Module testing.

The ACE system interfaces with the Apollo through carry on support equipment during prelaunch testing. Each ACE station connects to a computer complex which controls the flow of commands and data.

The lack of onboard checkout capability on Apollo resulted in the costly ACE complex which requires a large number of operators. A more sophisticated onboard system for Shuttle should make a large complex like ACE unnecessary. It may be, though, that a portion of ACE could be used by modifying it to interface with the Shuttle onboard system.

The present McDonnell Douglas Astronautics Company (MDAC) concept of Shuttle onboard checkout utilizes a digital computer and data bus. The onboard central computer complex (CCC) communicates to the subsystem LRU through a digital interface unit (DIU) which is connected to the CCC via the digital data bus. Two pairs of wires comprise the data bus, one for data and the other for a synchronizing signal.

The DIU recognizes a message directed to it from the CCC and converts the digital format into a signal type that the LRU can accept. The LRU response is then changed into the digital format by the DIU before being sent back to the CCC. Checkout data is integrated with operational traffic flow on the data bus which connects the CCC to many DIU's.

A DIU may be either area oriented and serve several LRU's or dedicated to a particular LRU. In the latter case, the DIU may be built into the LRU or attached to it. During checkout sequences, the DIU has the capability of multiplexing signals to and from a number of elements within each LRU.

The exact composition of the onboard checkout system for Shuttle has not yet been determined. Therefore, the complexity and capability of the CCC and the DIU's are not finalized. However, checkout techniques under study can be discussed and compared.

One onboard checkout method being considered is centralized checkout. With centralized checkout, the CCC analyzes the raw data from the DIU's to detect problems or trends. This can include voting the operational outputs of several redundant LRU's or LRU strings, reasonableness tests, and monitoring selected LRU parameters. Using a management by exception technique, the CCC then informs the crew of a problem or potential problem.

Instead of centralized checkout, a DIU may contain a microprocessor that can perform the checkout analysis. The DIU, after receiving a checkout command from the CCC, initiates a sequence to check the LRU(s). After receiving the checkout data the DIU analyzes the data and reports the status to the CCC.

Built in test (BIT) is another method of onboard checkout. The test circuitry is within the LRU (and possibly is a part of a DIU incorporated within an LRU). The BIT is stimulated by an external command or by out of tolerance LRU parameters. A method of BIT implementation is to provide two operational channels which are compared within the LRU. Unlike channel outputs cause a no-go signal to be sent.

Centralized checkout can allow the use of less complex DIU's, and off the shelf LRU's without BIT. System level tests are possible; the output from a string of LRU's can be analyzed by the CCC and is a good indication of proper operation.

BIT, on the other hand, enables problem isolation directly to the LRU. Checkout by BIT or a DIU microprocessor also requires less CCC capability and less complex software. LRU bench tests are simpler with BIT since BIT circuits perform part of the required testing.

Ground checkout using ground support equipment (GSE) is also possible with the data bus concept. Utilizing a ground interface with the data bus, the GSE can perform checkout similar to that of the CCC described above.

Even if GSE is used for ground test, there still must be enough inflight onboard checkout capability to determine a failure so that a redundant element can be switched into operation. Using centralized checkout, the redundancy switching level may be a string of LRU's which could necessitate extra ground tests to isolate a problem to one LRU.

The more comprehensive testing that may be required on the ground could be controlled by a ground processor that does not have the size and weight limitations of the CCC. Such detailed testing could be required during the maintenance cycle and in prelaunch hangar subsystem testing.

At the launch pad, there exists a need for ground executive control of the Shuttle even with an onboard checkout system. When no one is onboard during propellant loading and in case of an abort, certain onboard functions (and also ones on the ground) must be controlled.

A new GSE concept that may be applicable to Shuttle is that of Universal Test Equipment (UTE). The UTE would drive a ground data bus to control servicing and support equipment as well as interface with the onboard data bus. A minimum number of operators would be required because the UTE would display status rather

than all data available, be automated, and have self-test capability. Included in the UTE would be color graphic CRT's, a processor, and a keyboard for operator entry using a high level test language. A feature of UTE is that it could be used on any equipment that can interface to a DIU, and could be used for LRU and subsystem testing as well as for system checkout. For LRU testing, special test equipment may also be required to provide stimuli and monitoring.

Checkout, whether it be onboard or ground, results in the accumulation of data. In real time, the data is used by the checkout system to detect and isolate problems and to detect trends. An important ground function is to process stored data to provide trend analysis, especially for mechanical systems, and to keep a historical record of the LRU's. The history can be for each LRU as well as for each equipment type.

The handling of data will continue to be a large task. To reduce manual effort, it may be worthwhile to provide a computerized data bank for data reduction, compression, and storage. The data bank could be linked to UTE at the launch site area, the Shuttle factory areas, and possibly at certain vendors.

In addition to its data reduction role, the data bank could also be used to generate onboard and ground checkout programs by utilizing proper compiler software.

Avionic systems generally lend themselves to the checkout philosophy under discussion. However, fluid mechanical systems have traditionally been designed without interfacing capability with an electrical checkout system. For such a checkout method to be fully effective, new ideas for electrical stimuli and monitoring must be introduced into the design of valves, regulators, leak detection devices, etc.

FEASIBILITY OF AUTOMATIC FLUID MECHANICAL CHECKOUT AND SERVICING

Fluid mechanical systems have been one of the larger deterrents in achieving a complete autonomous onboard checkout system for space vehicles, particularly in the realm of self-test and fault isolation. The Space Shuttle autonomous onboard checkout and quick turnaround requirements challenge the fluid component industry to take a hard look at the current "state-of-the-art" and what must be accomplished in order to meet these new requirements.

Onboard monitoring of fluid systems during flight and automatic cryogenic servicing is within the present capability of most contractors. However, self-test and fault isolation to the LRU level is a problem area for fluid mechanical systems. The use of ground carts to supply stimuli for onboard tests is time consuming due to hookup time, verification of connections, and possible contamination of the onboard fluid systems. Additional test points must be incorporated into the system so that complete LRU test and fault isolation can be made. The use of onboard stimuli for fluid systems appears impractical, but this may be because we think of testing fluid systems with fluids. Let us envision the self-test of fluid systems through other means such as electrical correlation of mechanical movements, valve signature traces, ultrasonics, and thin film technology.

Thomas Crapper, the inventor of the valveless water waste preventer, advanced the state-of-the-art in his field. His ingenious solution, which can still be observed beneath the lid of most toilet tanks, depends upon a float, a metal arm, and a siphonic action to empty the reservoir. The degree of improvement over his original concept has been minimal. Recently, however, through the interest in ecology and the concern for conservation of water, a new concept utilizing a vacuum has been designed. Thus, an environmental concern stimulated new technology.

Now the need exists to advance the state-of-the-art of fluid components which will lend themselves to autonomous onboard checkout. Whose responsibility is this new requirement? The fluid component manufacturer, the major contractor, or the Government? It is the responsibility of all of us and in order to achieve the level which we are seeking we must pool our resources.

Automatic test capabilities must be designed into the vehicle system as a prime objective. The vehicle engineer can no longer design his system only for operational capabilities. The determination of the desired degree of autonomy, whether the vehicle design engineer realizes it or not, falls heavily in his lap. At the onset of a program, the vehicle system designer and ground support and test personnel must determine the degree of autonomy the project will achieve. Designers who achieved a level of success on past space programs must revamp their mode of thinking to design their components to accomplish the objectives of automatic checkout. Many vehicle system can be designed so that sensors, isolation valves, limit switches, flow devices, and transducers become an integral part of the LRU. Investigations must be made to determine the feasibility of testing fluid systems without the application of fluid stimuli from an external source.

The fluid industry shall remain behind in advancing the state-of-the-art only so long as the vehicle designers permit. In early space programs the design contractor's prime responsibility was limited to design of a lightweight, highly reliable operational system. The Space Shuttle program is the beginning of a whole new era which will emphasize reusable vehicles, self-test capabilities, fault isolation, and trend analysis. The airline industry years ago realized that in order to cut costs and reduce down time, spares, and ground test equipment, it had to implement a new concept of onboard testing as a matter of economic survival. The airlines have advanced the state of automatic checkout for their avionic systems and have improved the capability of monitoring nonelectronic systems. Fluid system designers, fluid component manufacturers, and their customer must now bring the level of self-test and fault isolation of fluid mechanical systems up to the level of the onboard avionic systems.

The Space Shuttle program must develop real time status monitoring techniques, automatic checkout capabilities, and fault isolation far advanced to that employed for any previous space program. No matter how advanced the computerized checkout system becomes, the subsystem cannot perform a real time status monitoring for automatic checkout unless the LRU can communicate its health status. During the design of fluid systems, every consideration of automatic test should be reviewed and implemented if desirable (See Figure I).

New methods of automatic testing and new concepts in fluid component and system design must be implemented. New concepts of testing fluid components using thin film transducers, secondary effects, leak detection, application of valve signature traces as a diagnostic tool, and electrical correlation of mechanical movement will be discussed. The purpose of this paper is not to resolve the problems of mechanical and fluid systems, but to discuss new test methods which may be **thought provoking**.

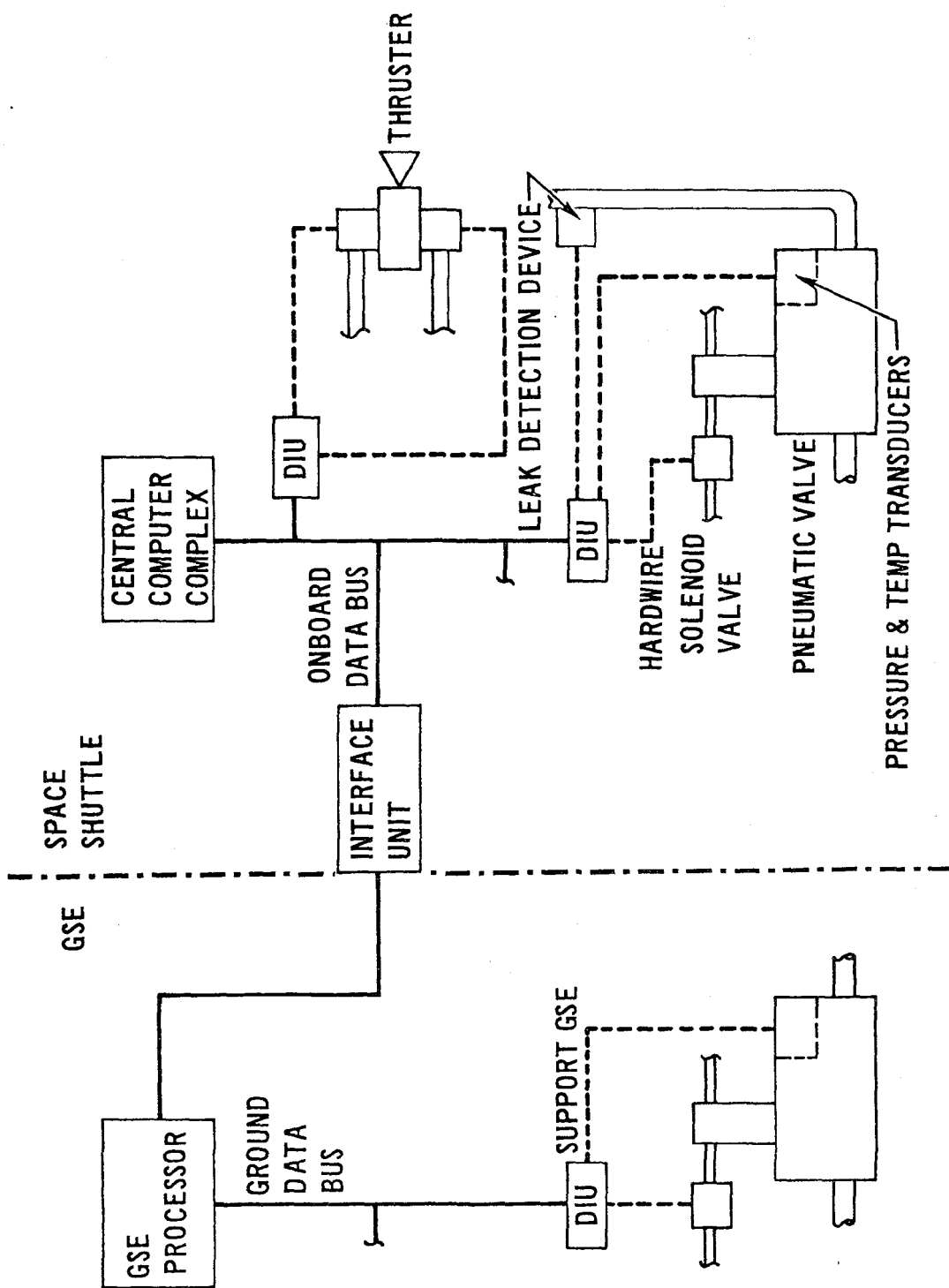


FIGURE I
ONBOARD/GROUND CHECKOUT SYSTEM

COMPONENT LRU DESIGN

The electronic "black box" concept which includes all the wonders of built in test and self-assessment should be applied to the fluid mechanical systems. During the design of fluid LRU's and subsystems, every consideration of automatic test should be implemented. Each LRU should be designed as a self-contained assembly which includes all flow, pressure, temperature, leakage sensors and test points. Pressure and temperature transducers should be combined into one unit to minimize entry points into the LRU.

The design of an LRU should be such that any part subject to failure may be replaced without removing the complete assembly. As an example, an LRU which contains a source regulator, relief valve, solenoid, or pneumatic actuated on/off valve should be designed such that the faulty seat or failed solenoid can be replaced without removing the LRU. This concept is somewhat of a "fix in place" method. If the LRU is designed so that seat and valve stem (which are the high fail rate items) are removable with the "fix in place" concept, spare parts cost, maintenance time of cutting, rewelding, X-rays, and possible contamination of the system would be tremendously reduced. For an assurance against leakage, fluid LRU's could be welded or brazed into the system. The LRU's could be designed to include the following considerations:

- (a) An ultrasonic device for flow and leak detection will provide flow data during flight and indicate flow and leakage for onboard testing, fault isolation, and trend analysis. These units are light in weight and do not require direct contact with the fluid media, thereby eliminating potential leak points.
- (b) Thin film transducers for pressure and temperature combined into a single unit are light in weight (approximately 1 ounce), are rugged, have better stability, and virtually no hysteresis. They can be welded in place, thereby eliminating potential leak points.
- (c) Valve signature traces of solenoids will provide trend analysis, solenoid operation characteristics, and add no additional weight to the LRU.

UTILIZATION OF SECONDARY EFFECTS FOR THE CHECKOUT OF NONELECTRONIC SYSTEMS

New techniques to permit a reduction in testing time, technical skills, and subsequent cost may be derived by utilizing secondary effects which accompany the operation of nonelectronic subsystems.

Secondary effects are those phenomena which result from the operation of a system or subsystem but are incidental to the primary purpose or mission. This particular category appears promising because it will disclose incipient or actual failures not otherwise possible with the more conventional primary stimuli and response checkout techniques.

The utilization of secondary side effects to determine system health is often employed by technicians. Overheated components detected as an odor or discoloration, and noticeable sound level changes caused by failing bearings are detectable side effects. A study by Illinois Institute of Technology² gave primary emphasis to secondary effects not requiring the physical dismantling of a system under test and not currently employed in existing checkout operation.

The techniques investigated include the use of acoustical, electromagnetic, chemical, and fine particle side effects. With all of these techniques, emphasis was placed on the use of natural spectrum signatures to determine the status of the system under test. In the areas of electromagnetic and chemical side effects, techniques that require the use of very simple built-in "seeds" for remote failure indicators were investigated to reduce dependence of natural spectrum signatures.

A review of current and past utilizations of secondary effects in the maintenance, repair, reliability, and quality assurance areas indicated that these effects are of great value in ascertaining the status of equipment. For the most part, however, these effects have not been methodically employed for the checkout purposes. It also appears that the utilization of secondary effects is of particular importance for the nonelectronic systems where built-in wire type communication paths do not exist. A wide variety of useful secondary effects exist, many of which can be utilized without extensive dismantling of the equipment. Probably one of the most important advantages of secondary effects utilization is the detection of precursors of malfunctions not otherwise possible. In the case of automatic checkout, the sensing of secondary effects can create an additional set of "pseudo test points" for a large variety of components which will be impractical to implement in the conventional checkout system.

VALVE SIGNATURE TRACES

Valve signature traces can demonstrate the health status of an electrically operated solenoid. Signature traces are established diagnostic tools for the determination of the existing and future performance of electrically operated fluid valves. Valves usually degrade relatively slowly to a point of malfunction, progressive galling, slow response, etc. The valve signature trace will provide information for a computer to determine the valve's health status. The information received from the signature traces can determine:

- (a) Electrical continuity
- (b) Valve opening and closing characteristics
- (c) Stuck or nonoperating valves
- (d) Sluggish valves
- (e) Valve simultaneity
- (f) Future performance predictions

A perfected analytical technique through the use of signature traces would conserve countless hours of manual test time.

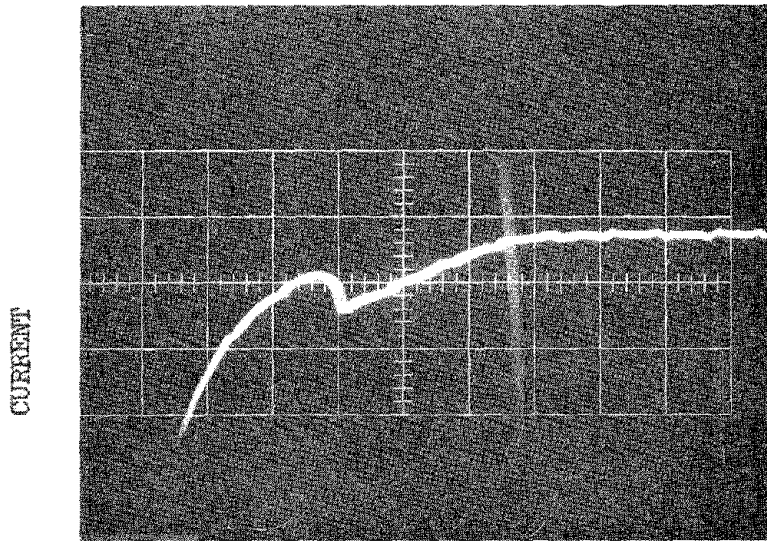
During valve signature sampling, a high sample rate is required because of the short current rise duration; this duration is dependent upon the size of and mechanical forces on the solenoid being tested.

When solenoid field strength is sufficient to overcome the poppet frictional forces, the poppet movement produces a counter electromotive force (EMF) which creates a negative slope ("glitch") in the current trace. This "glitch" is a detectable indication of the solenoid health status.

The MDAC-East - Aerospace Ground Equipment Engineering Department performed the following tests to indicate the feasibility of Valve Signature Traces.

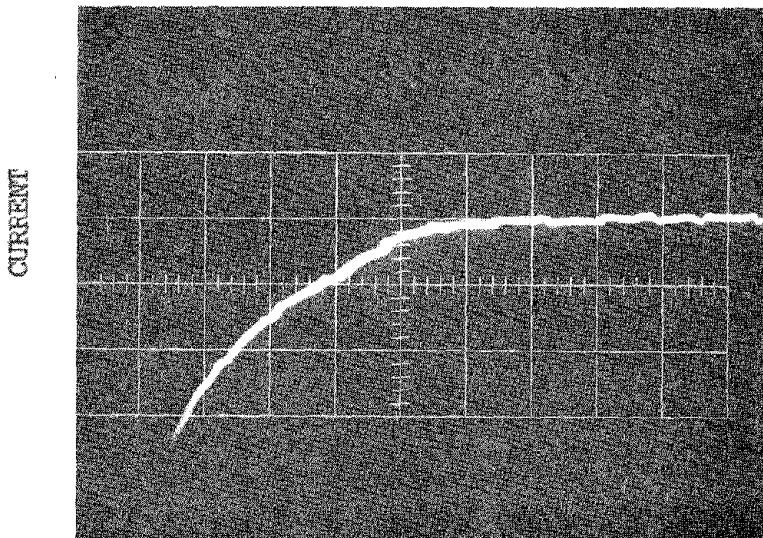
Figure II is a current trace of a normally operating solenoid valve; the negative trace or "glitch" indicates the poppet movement.

Figure III is a current trace of a failed or stuck valve. Note the smooth curve (absence of "glitch").



TIME (1 MSEC DIV)
NORMAL OPERATING SOLENOID VALVE

FIGURE II



TIME (1 MSEC DIV)
FAILED SOLENOID VALVE
(NOTE ABSENCE OF "GLITCH")

FIGURE III

Figure IV is a current trace of the same solenoid with added forces applied to the poppet. Note the additional amount of power and time that are required to move the poppet. This is one indication of a failing valve.

A conclusion from these tests is that the current traces are feasible and provide intelligent data but must be traced during the complete operation time span to be usable. The Space Shuttle orbiter and booster have approximately 400 electrically operated solenoid valves. Valve signature traces during the turnaround period with the utilization of a ground computer would give valuable information, and would take a matter of minutes to cycle all the Space Shuttle's electrically operated valves. Information received would be recorded in a data bank and compared as required.

LEAK DETECTION

Leak detection is a problem for all areas of space vehicle construction and test. Leak detection methods are determined by the type and size of the vehicle under test, the allowable leak rate, and the time available to test. Very minute allowable leak rates are associated with long space mission requirements and the hazardous propulsion fluids utilized. To meet the Space Shuttle turnaround requirements, new methods of assuring vehicle integrity through leak testing must be derived.

Normal leak test methods include pressure decay, bubbles, and mass spectrometer. However, new techniques uniquely suitable to Shuttle must be investigated.

SONIC AND ULTRASONIC TECHNIQUES

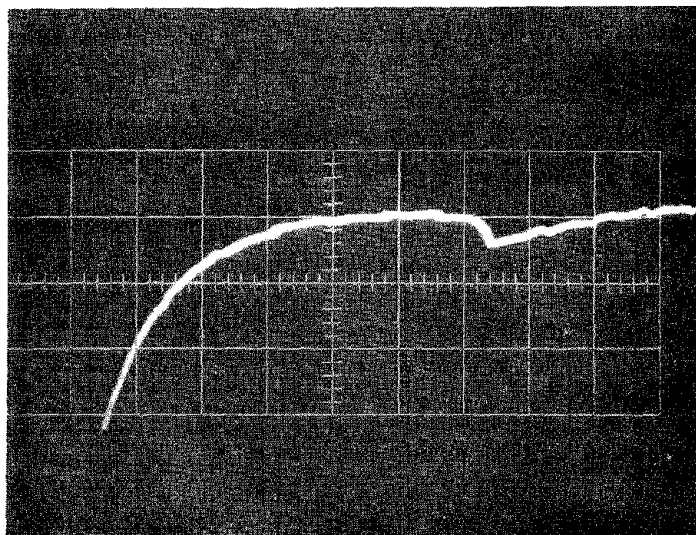
Acoustic techniques can be widely used for diagnostic purposes. Some sounds are very distinct and intense while others are very subtle. The high pitched sonic hiss caused by escaping compressed gas is quite unmistakable, while small leaks have been detected by measuring ultrasonic sound. Sonic/ultrasonic leak detectors can be made fairly sensitive and rugged without requiring skillful interpretation, and remote indication is feasible for many instances where ambient high frequency levels are not excessive.

Acoustic techniques utilizing ultrasonic flow meters have been used to measure flow velocity through pipes without touching the fluid. The propagation of sound is influenced by the motion of the media in which it travels. This effect can be monitored by simple vector addition of sound propagation velocity and flow velocity. Ultrasonic flow meters have rapid response and freedom from damage from cryogenic fluids. Erratic or nonfunctioning valves, intermittent pumps, and motor performance are all detectable with flow variation monitoring. The mechanical deterioration of components due to excessive wear, excessive vibration, etc., has been proven to be detectable. It appears feasible that acoustic techniques can be utilized in many areas of fluid mechanical systems to monitor health and perform trend analysis.

ULTRASONIC LEAK DETECTION

Ultrasonic leak detection techniques³ hold much promise for use on the booster and orbiter flight vehicles since these techniques will work equally well in the hard vacuum of outer space or for ground operations.

CURRENT



TIME (1 MSEC DIV)
FAILING SOLENOID VALVE
(NOTE ADDITIONAL POWER AND TIME REQUIRED TO MOVE POPPET)

FIGURE IV

Access to the orbiter and booster fluid lines during turnaround will be limited so an automatic checkout method must be developed. Suitable design and development work is required to adapt these techniques to Space Shuttle usage. Fixed sensors attached to the orbiter and booster fluid systems will enable leak detection and leak location. Fluid escaping through an orifice will generate sound waves that can be detected by the sensors, and the resultant output could be fed into the onboard or ground computer.

With the ultrasonic technique, leak detection can be accomplished during the vehicle maintenance cycle and during countdown prior to the next flight. Fixed sensors located on each side of flanges on relief valves and near critical components will also aid in satisfying the automatic checkout and fault isolation requirements. A sensor near a relief valve will indicate if the valve reseated in a leak tight condition after a functional test. Sensors will also verify valve seat condition without dismantling the system. Monitoring of flow and comparison with anticipated values yield information on satisfactory functioning of equipment.

NEW CONCEPTS IN LEAK DETECTION

A new concept of leak detection being investigated at MDAC-East considers the Space Shuttle's onboard leak detection method requirements of low weight and short test time. It utilizes a thermistor placed in the item under test. A change in temperature due to outside test vehicle environment and/or temperature change due to pneumatic expansion is proportional to the pressure increase within the test vehicle. The thermistor's resistance decreases in proportion to a temperature increase. A pressure sensor inserted within the vehicle tank transmits the summation of the pressure change due to temperature effect and pressure loss due to leakage. The resistance change from the thermistor and the summation of the pressure sensor is fed into a matrix bridge network where the variance in temperature will be added or subtracted from the pressure sensor output to indicate the quantitative gross leakage. (See Figure V)

The major advantages of this leak detection method are: electrical leak detection of pneumatic systems; temperature compensation; elimination of time expended for temperature stabilization; and leak detections performed in a maintenance area.

THIN FILM TRANSDUCERS

Unavailability of light reliable pressure sensors with good stability and low hysteresis has in the past limited use of onboard instrumentation. To verify system performance during test, transducers were often added, thus inducing a potential leak point and increasing system weight. Frequently just a pressure port was provided to interface with a transducer connected during ground testing and removed prior to flight.

A new development in the transducer field is the thin film transducer. In thin film transducers, ceramic films are vacuum deposited on pressure diaphragms, accelerometers, load cells, or beam-type pressure sensors. The strain gauge elements which form the transducer bridge are then deposited on the ceramic insulator. With the attachment of lead wires, the thin film sensors are ready to be packaged. At this point, sensors can be placed directly in the component or LRU, minimizing weight and potential leak points. Thin film transducers excel over conventional type transducers in stability, hysteresis, and linearity. This type of transducer will allow system designers to build in lightweight pressure monitor and test capabilities as an integral part of the system without degrading operational capability.

VEHICLE UNDER TEST

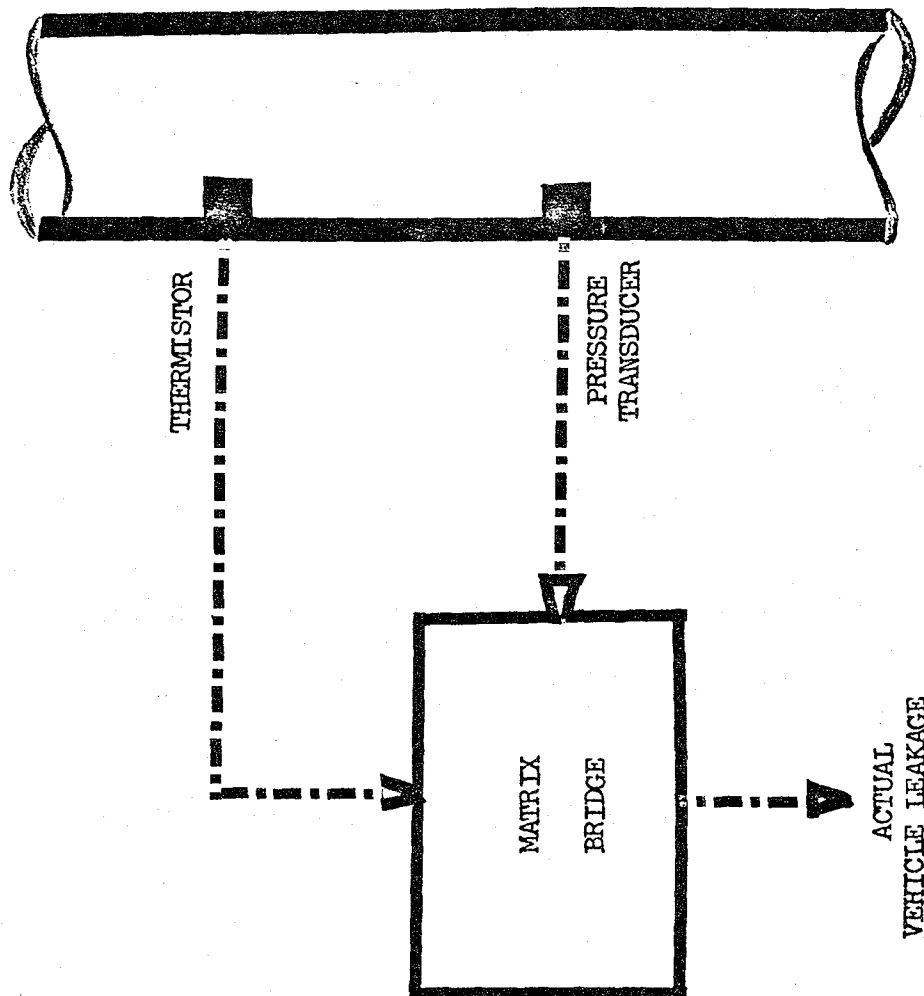


FIGURE V

LEAK DETECTION METHOD UNDER INVESTIGATION

AUTOMATIC CHECKOUT OF MECHANICAL COMPONENTS THROUGH ELECTRICAL CORRELATION

If complete autonomy with built-in vehicle stimuli is to become a reality, we might examine whether functional testing of fluid systems really requires an external pressure source. For example, is there a meaningful correlation between electrical input (stimuli) and a mechanical movement (output)? An electrical stimuli might be applied to the static fluid component under test and compared to the mechanical response. Through a series of tests, fluid system component characteristics may be established and subsequently correlated to the electrical stimuli allowing the observed fluid system response to be utilized for self-assessment and fault isolation. A planned test by MDAC-East involves incorporation of a solenoid on a relief valve to determine if the stimuli applied to the solenoid has a direct correlation to the force required to displace the relief valve spring poppet. The weight increase to the relief valve by the incorporation of a solenoid is at this time an unknown quantity, but if we do not venture into various experimental programs, we will never find methods of decreasing overall operational costs.

OTHER CONSIDERATIONS

In addition to the purely technical considerations of a spacecraft checkout philosophy, funding considerations and schedule milestones are interrelated as major controlling factors. For some requirements, such as an autonomous checkout capability while in space, no compromise is permissible. However, the cost penalties imposed by onboard checkout equipment must be determined and compared with the operational costs of a ground checkout approach. Development times may not be adequate to resolve the attendant problems associated with new test equipment or test methods, so that the more feasible approach might be to go with a less sophisticated checkout system and update flight and ground checkout equipment in a later version of the flight system. Studies should be of sufficient detail to identify advantages and disadvantages in specific meaningful terms such as "payload sacrifice per pound of onboard checkout equipment," "hours of ground turnaround time utilizing onboard checkout equipment," and "hours of ground turnaround time utilizing ground checkout equipment." These terms can all be related to dollars.

OPTIMUM SPACE SHUTTLE FLUID MECHANICAL GROUND CHECKOUT PHILOSOPHY

What is the optimum Space Shuttle fluid mechanical ground checkout philosophy? Somewhere in between the extremes of onboard/automatic and ground/manual checkout must lie the practical answer: how much testing should be done?

Past test philosophy has been one of test, test, retest, and test again. Highly reliable components have been designed for the various space programs and for the commercial airline industry. Let us use these components, restructure our thinking, and restrict our level of checkout to minimum essential levels as a start toward the optimum philosophy.

Secondly, we must continue to develop and use the computerized checkout techniques. The use of the computer has had dramatic impact on the Saturn/Apollo program. "The Saturn Ground Computer Checkout System checks valves, transistors, microelectronics, miles and miles of wiring, transducers, and all of the movable and nonmovable parts and circuitry in a real situation with each part operating in conjunction with all of the other eight million parts.

Four man-years of computational work are done in the relatively few hours of countdown before launch."⁴ Thirdly, we must utilize new checkout techniques. The Space Shuttle fluid mechanical systems require a high degree of onboard real time checkout, fault isolation, and readiness assessment. Application of secondary effects, signature traces, sonic and ultrasonic techniques, and built-in thin film transducers will help in achieving this capability, while having a negligible effect on vehicle systems weight or system reliability. A key factor is that, from the beginning, subsystem cost, weight, test parameters, automatic checkout, trend analysis, and operational capabilities must be part of the vehicle basic design concept. Evaluation groups consisting of flight test, operational, maintenance, GSE, and subsystem design personnel must take an active part in the design of the vehicle system if we are ever to reach our goal.

Reports made as long as 6 years ago by government and private institutions reveal a tremendous amount of study on automatic checkout of nonelectronic systems. The reports referenced herein are samples of the methods that can be utilized. However, if the system designers do not, or will not, investigate or implement these advancements, usable technology of automating fluid mechanical systems for checkout will remain static.

Our goal is a fully automated onboard checkout of fluid mechanical systems. Based on present levels of technology, cost limitations, and schedule considerations, we must approach this ideal goal in logical steps. The fluids industry must develop hardware capable of automatic checkout utilizing the previously mentioned techniques, and responsible contractors must continually strive for the fully automated fluid mechanical system.

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LOGIC DEVICES FOR THE READINESS ASSESSMENT OF MECHANICAL COMPONENTS

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ABSTRACT

This paper is directed toward definition of the logic device required for processing basic performance data originating at a mechanical line replaceable unit such as a pump, pneumatic regulator, valve, et al. Sensor data resulting from state-of-the-art instrumentation techniques were examined in detail to determine logic device physical and functional configuration. Functional integration of this concept is consistent with advanced checkout philosophies. Three logic device implementation concepts were considered, and each was found to have application depending upon mechanical component density, complexity, and/or similarity. Guidelines for application of each concept are discussed.

INTRODUCTION

Space programs of the post-Apollo generation include requirements for re-usable vehicles with a fast turn-around. These requirements impact the existing philosophy pertaining to vehicle launch and in-flight readiness. Maintenance and checkout time will be at a premium, not only for flight hardware, but also for the non-flight, real-time ground support equipment. Existing mechanical devices which are essential to both airborne and ground equipment operations do not have the capability to communicate required status parameters. Thus, techniques far superior to those used for previous space programs must be developed and implemented for mechanical device readiness assessment. These program requirements dictate the need for automatic, self-contained readiness assessment of ground and flight hardware.

While the capability for self-contained readiness assessment has existed and has been incorporated to varying degrees in electrical/electronic equipment for some time, little has been accomplished relative to mechanical components. Application of readiness assessment philosophy to mechanical components will provide operational status (go, no-go, caution) and maintenance information for critical Line Replaceable Units (LRU's). Selective instrumentation of the LRU's performance parameters, modified

by operational tolerances and coupled with a logic device, can provide this confidence data as well as "predict", detect, and isolate faults. In addition to providing component status data, the logic device will receive, decode, and process commands necessary for LRU control and will operate as an integral part of an overall system containing a number of varied, interrelated critical components. The specific functions to be accomplished by the logic device depend primarily upon the total system philosophy and complexity of those component parameters required for fault prediction.

Information contained in this paper was derived from the General Electric Company study performed (during the period April 21 through November 13, 1970) for the John F. Kennedy Space Center, "Techniques for Automatic Self-Contained Readiness Assessment and Fault Isolation for Ground and On-Board Mechanical Systems". All backup details are documented in Phases I and III Progress Reports 70-831-892 and 70-831-894, dated 20 July 1970 and 19 October 1970, respectively.

The objective of that study was to provide direction for achieving the technology by which mechanical devices' performance parameters or discriminants can automatically, and in real time, be determined and evaluated. The performance parameters include data required to check out and monitor these components as well as those needed to predict and isolate faults. Implementation of this technology will improve the capability for malfunction isolation and detection, permit maintenance on an "as required" basis rather than routinely, and reduce checkout time at a potentially lower cost with increased mission reliability.

REPRESENTATIVE MECHANICAL DEVICES

The approach of the General Electric Company study was to define those Saturn V mechanical components in use on Launch Complex 39 on-board and ground systems and to assume that the configuration of mechanical devices used on near-future space programs will have, for practical considerations, the same general functions and characteristics. Therefore, LC-39 mechanical device performance monitoring limitations must be resolved before mechanical readiness assessment of future space programs can be achieved.

Initially, a survey of Launch Complex 39 identified 183 on-board and ground systems, 42 of which were primarily mechanical. These systems were found to contain over 20,000 mechanical components representing 43 generic families such as accumulators, actuators, valves, etc.

Utilizing selection criteria tabulated in Table 1, 36 mechanical devices were selected as representative of the total population.

Table 1
Representative Mechanical Device Selection Criteria

<u>PRIMARY CONSIDERATIONS</u>	
●	WAS MECHANICAL DEVICE A LINE REPLACEABLE UNIT?
●	HAD SIMILAR LRU BEEN IDENTIFIED AS REPRESENTATIVE?
●	DID LRU HAVE A HIGH FAILURE RATE?
●	DID LRU REPRESENT A LARGE POPULATION?
●	WAS LRU VERY EXPENSIVE TO BUY OR REPAIR?
●	WAS LRU TIME CONSUMING TO REPAIR OR VERIFY STATUS?
<u>SECONDARY CONSIDERATIONS</u>	
●	LRU OPERATIONAL PRIORITY.
●	AVAILABILITY OF LRU DESCRIPTIVE DATA.
●	PREVENTIVE MAINTENANCE REQUIREMENTS.
●	FLOW MEDIUM AND ACTUATING INPUT.
●	REPAIR AND CHECKOUT TIME.

The numerical distribution of the representative mechanical devices selected, by generic family, was:

<u>Generic Family</u>	<u>Quantity</u>	<u>Generic Family</u>	<u>Quantity</u>
Accumulator	2	Fuse, Flo	1
Actuator	4	Heat Exchanger	1
Blower, Fan	1	Motor	2
Compressor	1	Pump	2
Controller	1	Regulator	3
Damper	1	Valve	15
Filter	2		

These 36 mechanical devices were subjected to a detailed analysis to establish functional parameters necessary for readiness assessment and fault isolation.

MECHANICAL DEVICE READINESS ASSESSMENT REQUIREMENTS

To ascertain whether a mechanical device is in a go, no-go, or caution status requires, first, an identification of those functional parameters which must be monitored to

determine readiness assessment. The information necessary to define readiness assessment requirements either in a static or dynamic operational state was found to include:

- a. Part Identification—The mechanical device (LRU) or piece part of the LRU under consideration, e.g., a valve or the poppet, ball, guide spring, etc., of a valve.
- b. Failure Mode—Particular form or manifestation of the LRU's inability to perform its expected action or function.
- c. Requirement Parameter—The most basic measurement which can be made to detect the failure mode under consideration.
- d. Parameter Limits—Prescribed boundaries which define go, no-go, and caution limits. These limits are not necessarily absolute values, but can be relative to some other parametric value.

A detailed analysis tabulating the above items was completed for each of the 36 representative mechanical devices which are representative of over 20,000 actual mechanical devices.

Seventeen separate requirement parameters were identified for the 36 representative components. The numerical commonality of these parameters is depicted in Figure 1. It should be noted that a specific parameter may occur in more than one manner for a given component and may represent vastly different properties in particular applications. For instance, the parameter of force may represent seal compression, torque, or actuator output force.

The representative mechanical devices examined possess typically from 4 to 10 of these parameters with 6 being the average number which must be evaluated to achieve total readiness assessment capability.

LOGIC DEVICE APPLICATION

The deployment of a logic device which will satisfy the overall functions of readiness assessment, monitoring, and controlling of critical components is dependent primarily on the overall system philosophy, component density, and similarities. Although there are many similarities between the three implementation concepts depicted in Figure 2, the logic device discussed herein is in reference to Concept 1 which utilizes a dedicated logic device for each critical component. The logic device described assumes that the included functions will be performed in close proximity to the mechanical component.

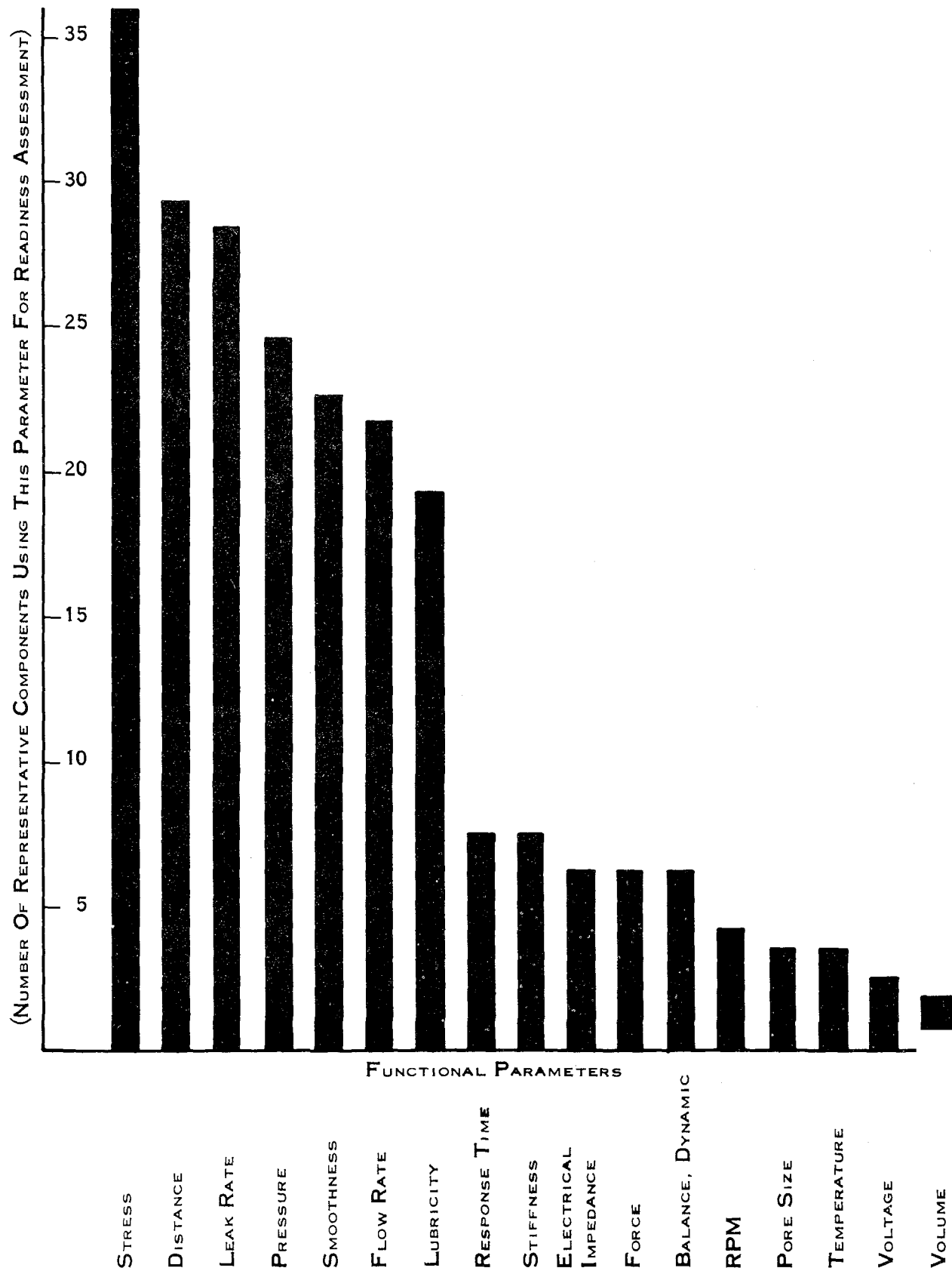
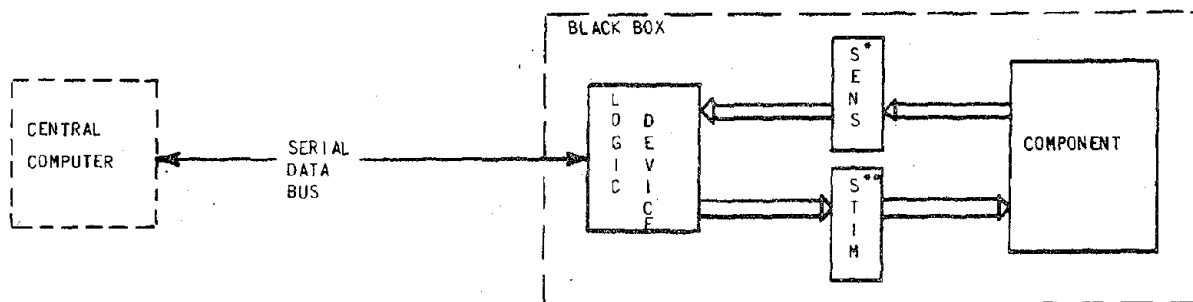
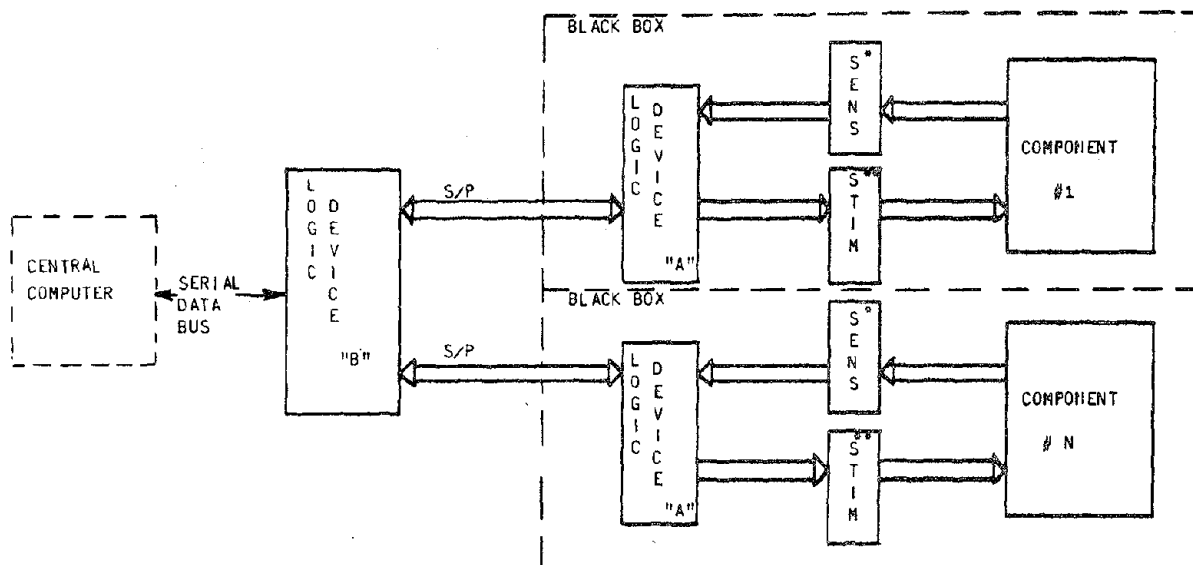


Figure 1. Parameters versus Frequency of Utilization

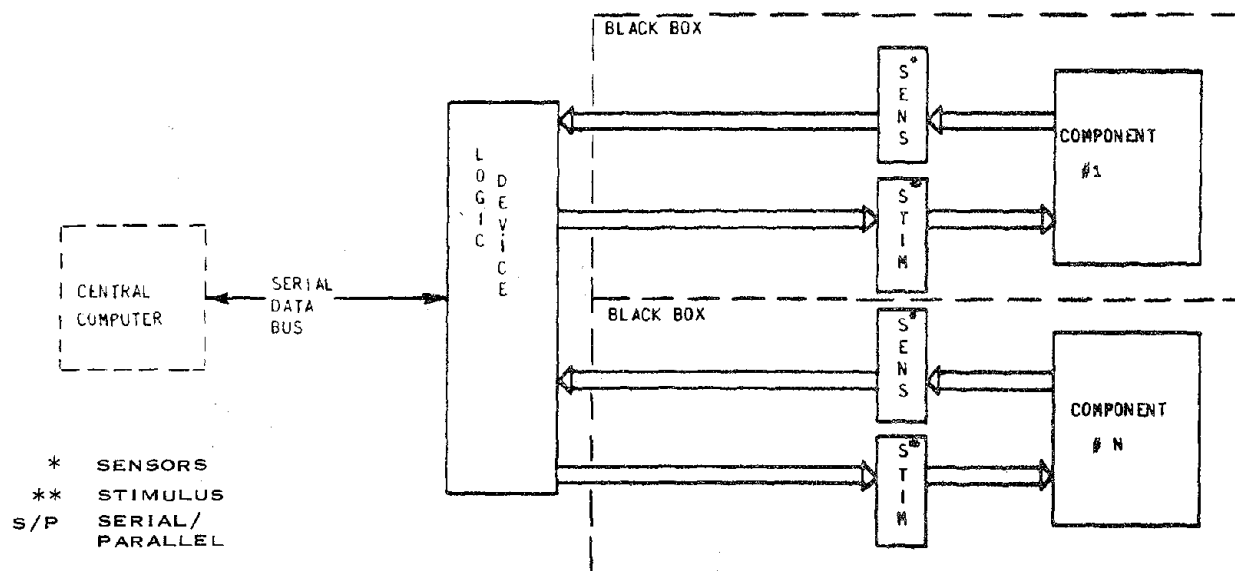
CONCEPT #1 - LOGIC DEVICE FOR EACH COMPONENT



CONCEPT #2 - LOGIC DEVICE FOR EACH COMPONENT
- LOGIC DEVICE FOR GROUPS OF COMPONENTS



CONCEPT #3 - LOGIC DEVICE FOR GROUPS OF COMPONENTS



* SENSORS
** STIMULUS
S/P SERIAL/
PARALLEL

CONFIGURATION CONCEPTS

Figure 2. Implementation Concepts

be established. Once this is done, test algorithms and limits can be selected with a good probability of success and can be then optimized experimentally.

Logic Device Status (Self-Test)

Each logic device will be capable of determining internal status and operational readiness by self-test.

Bidirectional Communications

The two-way communications function will be performed in a manner compatible with the existing data bus concept. The data bus concept is defined as a single cable which provides serial data transfer, in either direction, between any of the data bus parallel interfaces. The bidirectional communication function includes receiver, decoder, verification, transmission, control, and buffer subfunctions. The data bus could be redundant with appropriate encoding/decoding modifications to the bidirectional communication function.

Stimuli Generation and Distribution

Primary stimuli are the result of commands generated at an external source, received, decoded and verified via the bidirectional communication and then transferred to the distributor in a form ready for execution. Secondary stimuli are commands generated internal to the logic device and are necessary for stimulating the mechanical component for determining readiness. Both primary and secondary stimuli can be discrete or analog.

Measurement Acquisition and Data Processing

Accomplishing component readiness assessment is entirely dependent on determining the component status indicators, selecting the proper sensors, and then selecting the processing necessary to isolate the discriminant. A logic device discriminant is defined as processed information, derived from data collected at the component, that can be correlated to the performance and operational condition of the component.

Figure 4 represents discriminants based on three sensor categories, specialized analogs, analogs, and discrettes. The selection of the discriminants and transducers which will provide component readiness assessment varies from component to component. The General Electric Company study indicated that a typical component would require six monitoring points: 1 specialized analog, 2 analogs, and 3 discrettes.

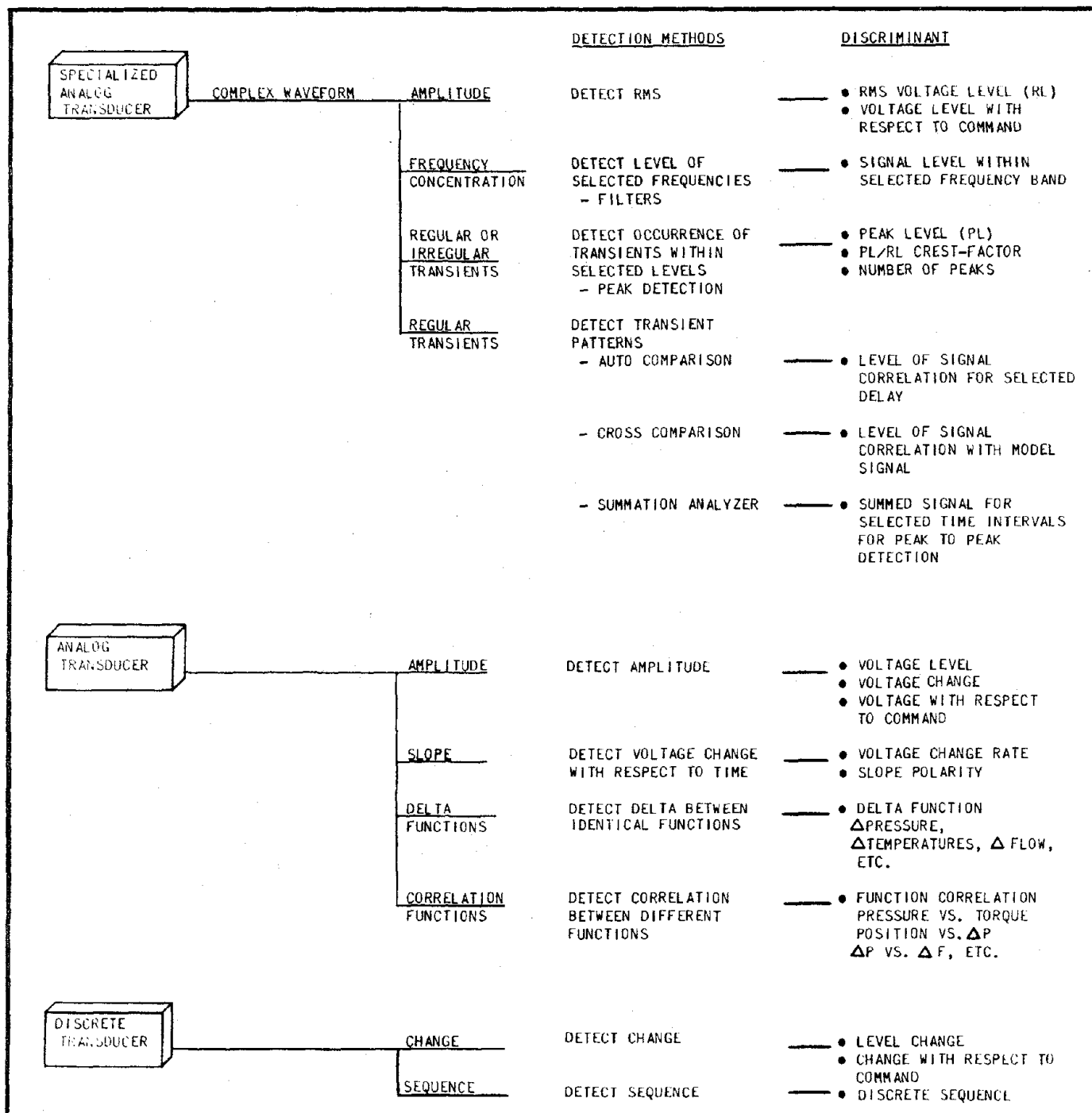


Figure 4. Identification of Discriminants

In many instances the same computation or preprocessing function could be performed with either analog or digital techniques. In these instances the logic device would utilize the technique or combination of techniques that best satisfy the design objective.

- a. Specialized Analogs—Specialized analogs are considered to be complex waveforms such as an accelerometer output used in structure borne acoustics with a frequency content of 0 to 50 kHz. Capability of the logic device includes the detection of:
 - RMS signal levels.
 - Signal levels within selected frequency bands.
 - Irregular transients.
 - Transient patterns.
- b. Analogs—Analogues in this category are considered to be of low frequency (0 to 1 kHz); such as those resulting from temperature, pressure, and flow sensors. Frequently, information pertaining to the mechanical component status, particularly fault prediction, can be determined by isolating those discriminants contained in low frequency analogs. Capability of the logic device includes the detection of:
 - Amplitude.
 - Slope.
 - Delta between identical functions.
 - Correlation between different functions.
- c. Discretes—Discretes in this category are considered to be event type such as those used for sensing discrete liquid level, valve closures, and other discrete sensors used primarily for component monitoring as opposed to readiness assessment. Capability of the logic device includes the detection of:
 - Discrete changes.
 - Discrete sequences.

LOGIC DEVICE PHYSICAL CHARACTERISTICS AND COST

The logic device is critical to the success of automatically determining component readiness. The logic device characteristics (size, weight, and power consumption) are critical in determining the application or deployment of the device in a total system. Because of this criticality, a "preliminary" assessment was made relative to its characteristics and material cost based on existing technology and off-the-shelf piece parts.

Characteristics and cost of the logic device are based on the logic device functional requirements previously discussed and the assumptions and supporting rationale utilized to establish the characteristics which follow:

- a. Logic Device Processing Capability—The capability of the device was defined to satisfy the processing requirements for one relatively complex component, requiring those diagnostic routines necessary to identify the discriminants as depicted in Figure 4.
- b. Dedication of Logic Device—For the purpose of this exercise, the logic device was considered to be dedicated to the component (i.e., Concept 1). The logic device would be capable of processing:
 - 6 Transducer Inputs:
 - 1 Specialized analog.
 - 2 Low frequency analogs.
 - 3 Discretes.
 - 4 Output Commands:
 - 2 Analog stimuli.
 - 2 Discrete stimuli.
 - 1 Serial Bidirectional Digital Data Bus Interface with:
 - Multiple inputs (commands).
 - Multiple outputs (status, performance data).
- c. Building Block Construction—The logic device would be developed from a family of functional modules which will take maximum advantage of the rapidly improving large-scale integration semiconductor technology.
- d. Modular Organization—The logic device would be organized in a modular arrangement employing a minimum number of unique building block modules. The functional modularity will provide overall logic device flexibility by permitting incremental configurations that would satisfy specific operational and component readiness assessment requirements.
- e. Memory Selection—Based on the functional requirements, a combination of Read-Only-Memory (ROM) and Random-Access-Memory (RAM) was selected. The selection criteria utilized was power consumption, size, cost, and speed although speed was not a major consideration. The selection resulted in 2048 8-bit words of static metal-oxide semiconductor RAM and 2048 8-bit words of ROM.
- f. Stimuli Distribution—Stimuli, both analog and discrete, would be limited to 100 milliamperes from the logic device. For those stimuli requiring additional power, the logic device will provide a pilot control to a stimuli power source external to the logic device.

- g. Storage—No off-line storage will be required by the logic device. Long-term trend analysis will be accomplished by a higher level computational device.
- h. Piece Part Selection—Only off-the-shelf piece parts were selected, and quantity purchase prices were used.
- i. Power—Regulated ± 15 volts and +5 volts will be provided to the logic device.
- j. Analog Conversion—Analog signals were converted to 8-bit binary coded decimal form. The 8-bit resolution or an output accuracy of ± 0.4 percent was felt to be adequate for a majority of the applications.

Table 3 depicts the summary results of this exercise broken down by functional elements of the logic device.

Table 3
Logic Device Characteristics and Cost

FUNCTION	SIZE (CUBIC INCHES)	WEIGHT (POUNDS)	POWER (WATTS)	MATERIAL COST ESTIMATES (DOLLARS)
BIDIRECTIONAL COMMUNICATION	16	0.5	1	500.00
STIMULI GENERATION AND DIST.	8	0.3	1	200.00
PROCESSING	64	4.0	4	2,000.00
MEASUREMENT ACQUISITION	34	2.4	7.4	1,150.00
MEMORY	20	1.0	13	1,700.00
SELF-TEST	8	0.3	1	250.00
PACKAGING	<u>64</u>	<u>1.0</u>	<u>—</u>	<u>500.00</u>
TOTAL	214	9.5	27.4	6,300.00

CONCLUSIONS

None of the representative mechanical components was determined to be completely adaptable to readiness assessment by use of existing evaluation techniques. The range of adaptability was from 29 percent to 89 percent with the average being 70 percent. Looking at the total group, an additional 25 percent can potentially be obtained by development and application of new techniques; 4 percent can potentially be obtained by component redesign; and 1 percent can be obtained by performance of the function by alternative methods. Figure 5 displays the relative measure of achievement of readiness assessment by each of these methods.

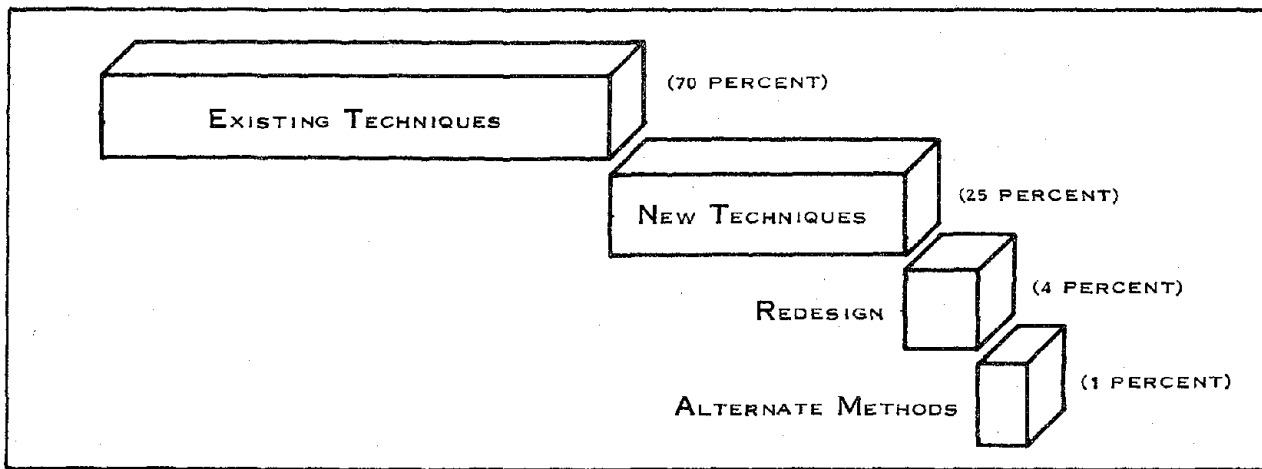


Figure 5. Methods for Achieving Mechanical Readiness Assessment

While in theory, all of the representative components have the potential of being completely adaptable to automatic readiness assessment, this claim must be qualified. First, considerable development work must be done to advance techniques such as ultrasonic imaging, optical interferometry, and pattern recognition of images before they can be utilized in many of the applications. Second, to achieve problem detection and malfunction prediction in a meaningful manner, extensive testing of the various mechanical devices will be required in order to identify the significant discriminants.

A quantitative evaluation or comparison of the discriminants must also be made; that is, what size fault can be detected, what size fault is significant in each particular case, and at what rate will a detectable fault degenerate to a no-go condition?

The logic device hardware and technology presently exist to accomplish mechanical device readiness assessment. Minimum packaging size would be approximately 210 cubic inches, cost (in production quantities including manufacturing) would be about \$12,000 each, and each would consume 27 watts of power.

A reduction in logic device size, weight, and power consumption could be made possible by:

- a. The development of large-scale integrated circuits and hybrids specifically tailored to the logic device application.
- b. Dedicating the design for each logic device to satisfy a specific mechanical component.

The first approach is recommended because it would significantly reduce the physical characteristics of the logic device and because the developmental cost could be amortized over many logic devices. The latter approach is not recommended primarily from the standpoint of the expense incurred for the design and development of many special-purpose logic devices.

State-of-the-art technology is changing rapidly in the area of semiconductors; making possible, in the next year or two, the development of logic devices with increased performance and reliability, while undergoing an estimated 30 percent reduction in package size, weight, and power consumption.

System concepts may dictate that much of the processing function should be accomplished in a centralized processor as depicted in Concepts 2 and 3. Table 2 highlights the conceptual differences.

The typical application of the logic device may require varying degrees of dedication, measurement acquisition, and processing capability. For this reason, the logic device design should be modularized, to the extent possible, such that the logic device configuration can be selected based on the LRU requirements for readiness assessment.

LOGIC DEVICE FUNCTIONS

Mechanical device readiness assessment parameters can be selected, and instrumentation is available, or can be developed, to provide electronic presentation of those parameters; however, processing and interpretation of this data, to translate it into meaningful go, no-go caution signals, must employ digital logic.

The logic device provides those functions necessary to automatically determine the operational status of the mechanical component. These functions are:

- Measurement Acquisition.
- Data Processing.
- Status Processing.
- Memory and Software.
- Self-Test.
- Bidirectional Communications.
- Stimuli Generation and Distribution.

Figure 3 depicts the logic device and its functional interfaces.

LOGIC DEVICE CAPABILITY

Status Processing

Status processing functions within the logic device will provide the component status continuously or when requested by an external source. The component status will be one of go, no-go, and caution. The status of the component will be formatted into a digital word compatible with data bus techniques. The go status indicates that the component is well and that no degradation has been sensed either by direct measurement or by the diagnostic routines within the logic device.

Table 2
Concept Matrix

CRITERIA	CONCEPTS		
	CONCEPT #1	CONCEPT #2	CONCEPT #3
READINESS DETERMINED AT COMPONENT	READINESS WOULD BE DETERMINED AT THE COMPONENT.	READINESS WOULD BE DETERMINED BY LOGIC DEVICE "B" SERVING SEVERAL COMPONENTS.	READINESS WOULD BE DETERMINED BY LOGIC DEVICE SERVING SEVERAL COMPONENTS.
STANDARDIZATION AND MODULAR TECHNIQUES	COMPATIBLE WITH MODULAR TECHNIQUES. LOGIC DEVICE WILL BE UNIQUE FOR EACH TYPE COMPONENT.	COMPATIBLE WITH MODULAR TECHNIQUES. LOGIC DEVICE "A" WILL BE UNIQUE FOR EACH TYPE COMPONENT. LOGIC DEVICE "B" COULD BE GENERALLY STANDARDIZED.	COMPATIBLE WITH MODULAR TECHNIQUES. LOGIC DEVICE COULD GENERALLY BE STANDARDIZED PENDING APPLICATION AND SIGNAL CONDITIONING REQUIREMENTS.
SIZE & WEIGHT PER COMPONENT MONITORED	LARGEST	REDUCED BY DEGREE IN WHICH TIME SHARING IS UTILIZED.	REDUCED BY DEGREE OF WHICH TIME SHARING IS UTILIZED.
COST	HIGHEST COST - EACH LOGIC DEVICE REQUIRES TOTAL FUNCTIONS FOR COMPONENT ASSESSMENT.	REDUCED TO THE DEGREE IN WHICH THE COMPONENTS TIME SHARE LOGIC DEVICE "B".	REDUCED TO THE DEGREE IN WHICH LOGIC DEVICE AND SIGNAL COND. IS TIME SHARED.
SENSOR TYPES	CAPABLE OF HANDLING STATE-OF-THE-ART SENSORS. LOGIC DEVICE IS DEDICATED TO COMPONENT.	CAPABLE OF HANDLING STATE-OF-THE-ART SENSORS. LIMITED BY NUMBER OF ROUTINES REQUIRED TO ASSESS COMPONENTS.	CAPABLE OF HANDLING STATE-OF-THE-ART SENSORS. LIMITED BY NUMBER OF SENSOR TYPES AND LOGIC ROUTINES REQUIRED TO ASSESS COMPONENTS.
DIAGNOSTIC ROUTINES REQUIRED	NO TIME SHARING OF IDENTICAL DIAGNOSTIC ROUTINES BETWEEN COMPONENTS.	DIAGNOSTIC ROUTINES COULD BE TIME SHARED WITH MANY COMPONENTS.	DIAGNOSTIC ROUTINES COULD BE TIME SHARED WITH MANY COMPONENTS.
DATA BUS CONCEPT UTILIZATION	WOULD UTILIZE CONCEPT AND WOULD BEST BE SUITED TO WIDELY SEPARATED COMPONENTS.	WOULD UTILIZE DATA BUS CONCEPT. INTERFACE BETWEEN LOGIC DEVICE "A" AND "B" IS SERIAL/PARALLEL.	WOULD UTILIZE DATA BUS CONCEPT BETWEEN LOGIC DEVICE AND CENTRAL COMPUTER ONLY - REMAINING INTERFACES ARE PARALLEL.
COMPONENT DENSITY	WOULD BE IDEAL FOR VERY LOW DENSITY, VERY COMPLEX COMPONENTS.	WELL SUITED FOR HIGH DENSITY COMPONENTS USING UNIQUE SENSING TECHNIQUES.	WELL SUITED FOR HIGH DENSITY COMPONENTS WITH IDENTICAL SENSING TECHNIQUES. SIGNAL CONDITIONING COULD BE TIME SHARED AT THE LOGIC DEVICE.

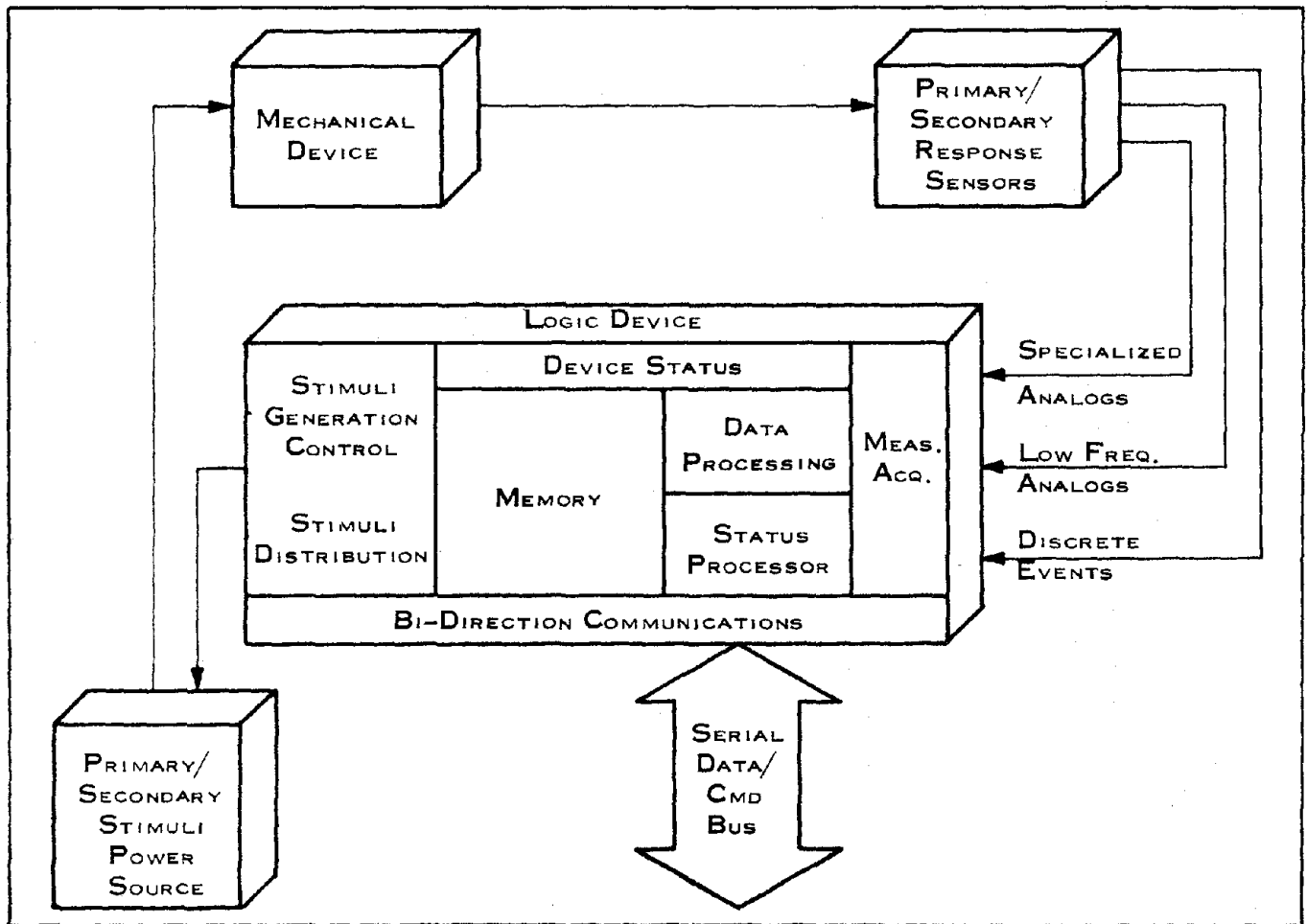


Figure 3. Logic Device Functional Interfaces

The caution status indicates that component performance degradation has been sensed either by direct measurement or by diagnostic routines. The caution status further indicates that the component is still capable of performing its intended function within its operational limits. The caution status will be accompanied by an explanation identifying the component approaching possible malfunction and the cause, determined by the logic device, thus providing fault prediction at the component or line replaceable unit level.

The no-go status indicates that the component is not capable of operating within normal operational limits. The no-go status will be accompanied by an identification of the malfunctioned component and the cause, determined by the logic device, thus providing fault isolation at the component or LRU level.

Memory and Software

Memory and software contained within the logic device must be adequate to accomplish the processing functions. This includes memory for program storage as well as data storage for stimulus distribution and generation, measurement acquisition, data processing, status processing, bidirectional communication, and logic device self-test.

Because of the number of sensor techniques and the processing techniques required to assess the readiness of a given component, the software development will require an extensive verification program to thoroughly evaluate the logic device-mechanical component relationship. This evaluation will be necessary to confirm the test point location, sensor selection (sensitivity and selectivity), diagnostic routines, signal conditioning, stimulus generation, and the overall ability of the logic device to assess the readiness, predict failures, and isolate the fault. Complete specifications of test algorithms will require that special attention be given to each logic device input when component assessment is completely automated.

Problems can be anticipated in the generation of algorithm specification. It is generally difficult to specify necessary and sufficient test conditions or limits for all possible states that may exist. Further, there are no clear-cut rules or guidelines as to what constitutes a reasonable limit specification, as an example, complex wave-form analysis. This means that the logic device must have the necessary flexibility to meet unspecified requirements with a minimum effort. Experience with logic devices indicates that programmable memory may be replaced with Read Only Memory (ROM) at that point in time that the full test and diagnostic procedures for a particular device have been tested, tried, and found to be true.

Finding the most effective discriminant or discriminants for each mechanical component, in the operational environment, is a problem having two basic solutions. Statistically, if a sufficiently large sample of signatures from good and malfunctioning components is available, it is possible to evaluate a number of discriminants and to select the most effective. The success of this approach depends entirely upon a good statistical sample. In many cases, such a sample is not available or would be unreasonably expensive to obtain. A second approach is based on the understanding of the mechanical component and the process by which a particular signature is generated. This usually requires a thorough study of the mechanics of the component, operational characteristics, and environment, so that a model for normal and abnormal signatures can

A STUDY OF TECHNIQUES FOR THE AUTOMATED VERIFICATION OF REDUNDANCY

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INTRODUCTION

This presentation is concerned with the problem of verifying the operation of equipments in redundant configurations. The facts presented are essentially those developed by a NASA-sponsored study addressing this problem. See Figure 1.

The presenter was Dr. Alan Ford, of Radiation Incorporated, who served as study director on that study.

The work presented here was sponsored
by the Kennedy Space Center, Florida.
The work was performed by the Systems
Division of Radiation Incorporated,
Melbourne, Florida under Contract
NAS10-7072

REDUNDANCY VERIFICATION WITHOUT DISRUPTING SYSTEMS

SPONSORSHIP

Kennedy Space Center
NAS 10-7072

INVESTIGATION

Radiation Incorporated
Melbourne, Florida

Figure 1

DISCUSSION

The stringent requirements placed on equipment reliability and availability by operations such as that of the space shuttle necessitate the extensive use of redundant equipments. While reliability goals may be apparently achieved by increasing redundancy, in practice, the attendant increase in system complexity may tend to degrade the accuracy of knowledge concerning system readiness. This knowledge may be required for mission planning, such as abort or go-no-go decisions, for decisions concerning whether to go to a backup system -- and if so which system, or for maintenance purposes.

Where one-shot missions are concerned, repetitive checkout is not required and long count-down periods allow redundant equipments to be verified individually, with any system reconfiguration which is necessary for checkout being perfectly allowable. Indeed, in many instances, checkout of redundant equipment after installation may not be necessary at all. See Figure 2.

However, in the cases of ground support equipment which is employed on a repetitive basis and of reusable spacecraft, periodic checkout becomes a requirement. Furthermore, short turnaround times and the desire to make near real-time decisions on equipment performance for mission planning purposes in large part rule out the option of reconfiguring systems for checkout. These considerations have prompted the investigations reported here.

The problem addressed here is that of gaining status information concerning redundant equipments. Knowledge of status maybe required for mission planning, such as go, no-go decisions, determinations of when to go to a backup systems and to which system to resort, and for maintenance purposes.

PROBLEM

- **REUSABLE REDUNDANT EQUIPMENT**

FUEL VALVES

HOLD-DOWN ARMS

COMMUNICATIONS DEVICES

DATA TRANSFER DEVICES

- **KNOWLEDGE OF STATUS NEEDED**

MISSION PLANNING

USE OF BACKUP SYSTEMS

MAINTENANCE PURPOSES

Figure 2

While several varieties of checkout equipment are presently in use, it is true that none are capable of verifying redundancy without disrupting the system. See Figure 3. In general, they are capable of assuring that a function is available, but where several items are capable of performing the same function, no indication of which ones or how many of those items stand ready to properly execute the function may be derived. The major questions to be answered then are the following: See Figure 4.

- a. Among existing equipments, which are adaptable to redundancy verification?
- b. What methods of verification are to be favored and what are the advantages among the various techniques?
- c. What features should be incorporated into redundant designs in order to assure that the resulting equipments will be verifiable?

As a first step, consider the features which characterize a redundancy design. The list includes load sharing, degree of redundancy, distinguishable outputs, recovery time, and numerous others. See Figure 5. When such a list is investigated item by item, it is discovered that only four features require attention in order to consider a redundant configuration with regard to its verification. These are: See Figure 6.

Short turnaround times, such as those associated with shuttle operation, force a need for status verification without system reconfiguration. No existing equipment is capable of verifying the level of redundancy present or operating.

VERIFICATION WITHOUT DISRUPTING SYSTEMS

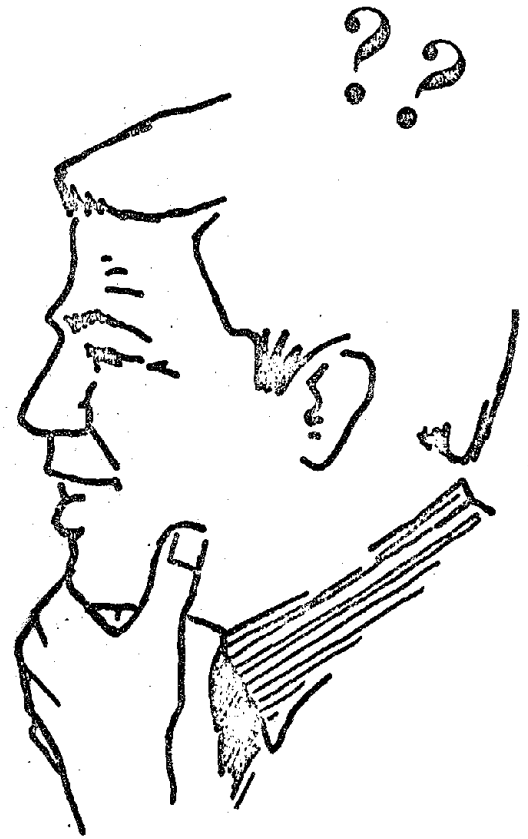
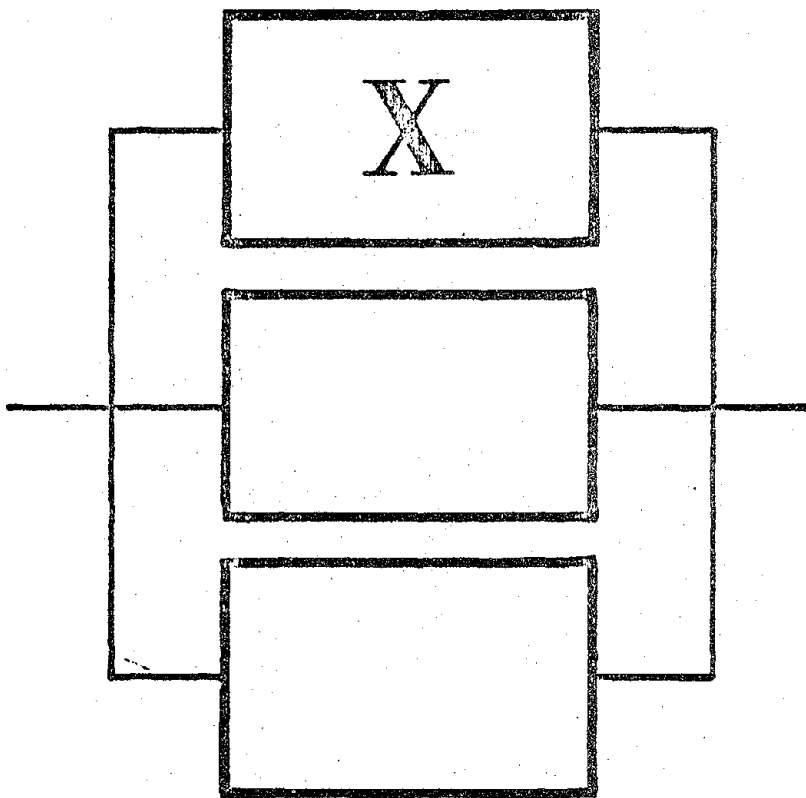


Figure 3

The questions presented are:

- a) Of existing equipments, which are adaptable to verification?
- b) What verification methods are to be favored and what are the relative advantages among the techniques available?
- c) What design features should be sought in future equipment procurements in order to assure adaptability to verification equipment?

QUESTIONS

1. EXISTING EQUIPMENTS ADAPTABLE?
2. VERIFICATION METHODS TO BE FAVORED?
ADVANTAGES AMONG VERIFICATION
TECHNIQUES?
3. DESIGN FEATURES TO ASSURE
ADAPTABILITY?

Figure 4

One may compile a long list of features which characterize a redundancy design.

FEATURES WHICH CHARACTERIZE A REDUNDANCY DESIGN

Load Sharing

Distinguishable Outputs

Back-up Capability

Recovery Time

Etc.

Figure 5

Only four of the many features are important for the purpose of verification.

FEATURES IMPORTANT TO VERIFICATION

- Distinguishable Outputs
- Failure Detect Scheme
- Verification Policy
- Output Variation

Figure 6

Distinguishable Outputs

Whether the individual outputs of the several redundant items can be distinguished one from the other has a heavy influence on the verification of those items. If only a common output from a group of redundant equipments is available, for one thing, it is obviously impossible to trace a failure to one of those items.

Output Variation

It is important to know whether the output of a redundant set of equipment varies with the number of properly operating elements of that set.

Verification Policy

Whether it is necessary to perform verification on a continuous basis or only on a periodic basis will influence verification design.

Failure Detect Scheme

The verification approach will be influenced by requirements imposed as a result of the failure detect scheme; i.e., it is desired to know the status of each element or only that a given level of operating redundancy is available (perhaps two out of three).

Of these four features, only two, distinguishable outputs and output variation are intrinsic to the redundancy design. The other two are fixed by the requirement of the verification process.

By setting up a dichotomous situation with regard to each of the four features above and enumerating all the possible combinations of features, mutually exclusive classes for redundancy (with respect to the needs of verification) may be established. These classes are defined in Figure 7. The figure should be read, for example, as a class A situation being one wherein the outputs/effects of each redundant element are distinguishable, it is required only to know the number of operable elements and not the status of each element, continuous verification is required, and the output of the redundant set varies with the number of operational elements in the set. Several combinations of features lead to situations which are inherently unverifiable. These situations have been lumped together into class H. These definitions are important in that they form a basis for discussing redundant situations which is independent of the function and form of the redundant elements and in that unverifiable situations are identified.

A design process, a general approach to the problem of designing a verification system has been defined. The process is outlined in Figure 8. An important feature of the process is the basic division of the problem into two problems, the set problem and the group problem. While no formal definition will be offered here, the group problem is the large,

Classes for redundant equipment may be established in terms of their characterization by the four features previously mentioned. This leads to the identification of situations which are inherently unverifiable.

C L A S S	Distinguishable Outputs/Effects		Failure Detect Scheme		Verification Policy		Variation of Set Output With No. of Oper. Elements	
	Outputs/Effects of each element are distinguishable	Outputs/Effects of each element are not distinguishable	Approach to detect the number of redundant elements operable	Approach to indicate status of each element	Verification performed on a continuous basis	Verification not performed on a continuous basis	Set output varies detectably with number of operational elements in the set	Set output does not vary detectably with number of operational elements in the set
A	X		X		X		X	
B	X		X		X			X
C	X		X			X	X	
D	X		X			X		X
E	X			X	X		DON'T CARE	
F	X			X		X	DON'T CARE	
G		X	X		X		X	
H	NOT VERIFIABLE UNDER REDUNDANCY FEATURES							

Figure 7

A general process for designing verification equipment has been established. The overall problem may be treated either as a set problem or as a group problem. Its treatment as one or the other of these will be dictated by characteristics of the redundancy to be verified.

***VERIFICATION
DESIGN PROCESS***

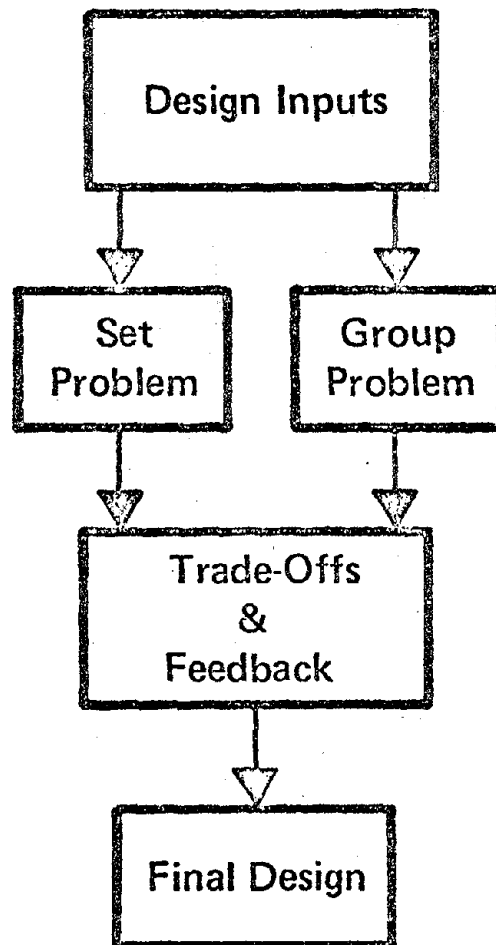


Figure 8

general problem (a group may contain several separate occurrences of redundancy and some may be internal to others) and the set problem is the special, but frequently encountered, problem of a single occurrence of redundant equipment which may be verified independent of other occurrences of redundancy. See Figure 9. A group may contain several sets but not vice versa. As an example, three logic modules arranged in a majority voting manner would constitute a simple set. It is the set problem which has received the most attention in this work.

By considering what is truly necessary to derive a statement of operational integrity of redundant equipments, a general model for the verification process has been developed. This model pictures the process as consisting of five functions. See Figure 10. The first of these is Coincidence Development, where some type of comparison is formed. The second is Parameter Estimation, basically a smoothing operation. The third function is Mapping to Conditional Status. In this function, a statement of operational integrity is arrived at from the information developed in the two previous functions. This statement must be made on a conditional basis in many cases, because, for example, a "bad" output can be taken as an indication of improperly operating equipment only if it is known that the input to that equipment is "good." Rather obviously, then, the fourth function is that of Status Resolution, a function which removes conditionality from the statement. The fifth and final function is that of Status Reporting; it encompasses the machine/man interface. The function of Coincidence

A simple set of redundant equipment contains no redundancy within any given element. A group of redundant equipment may contain several various occurrences of redundancy.

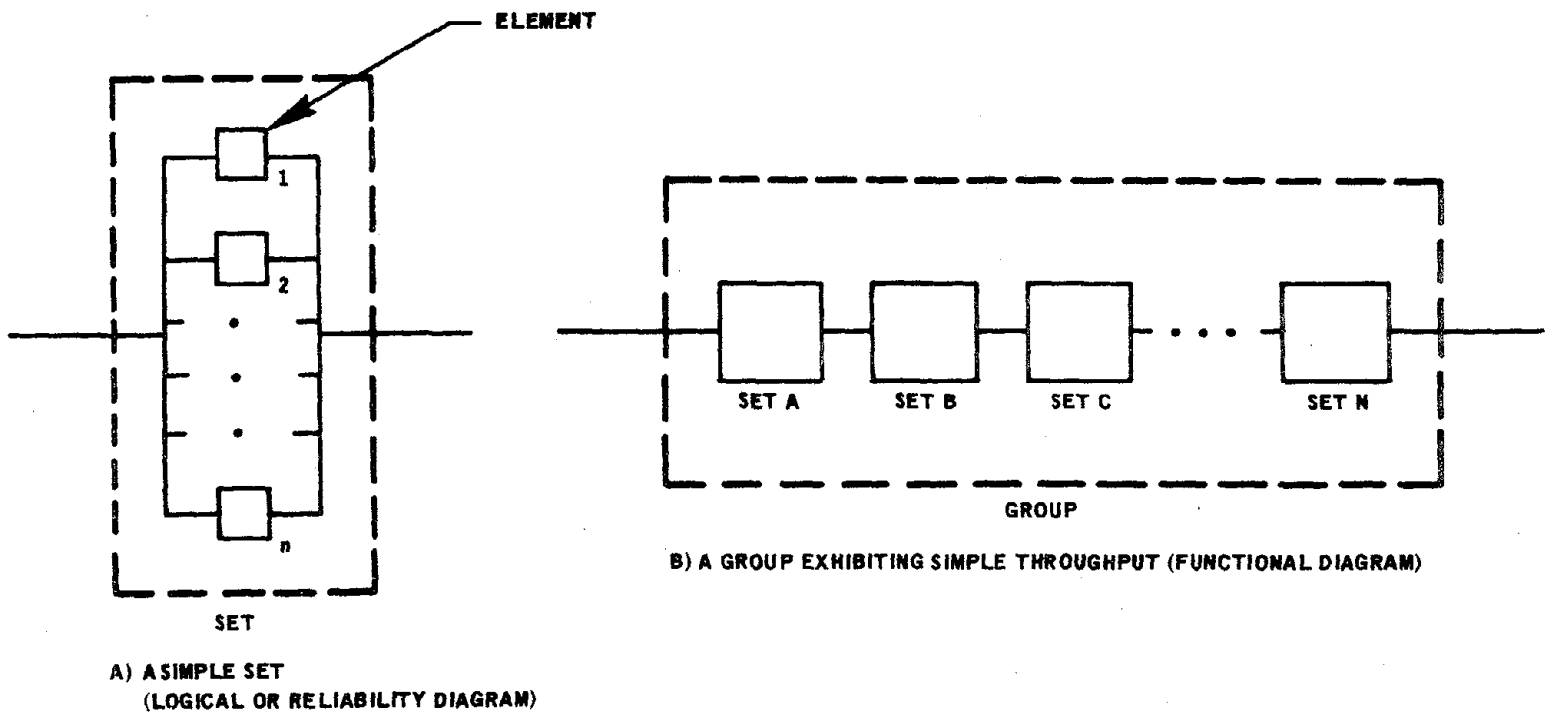


Figure 9

The process of redundancy verification may be viewed as consisting of five functions. These functions are Coincidence Development, Parameter Estimation, Mapping to Conditional Status, Status Resolution, and Status Reporting.

The term conditional refers to the fact that a "bad" output should be interpreted to indicate equipment which is not properly functioning only if the status of the input to that equipment is known.

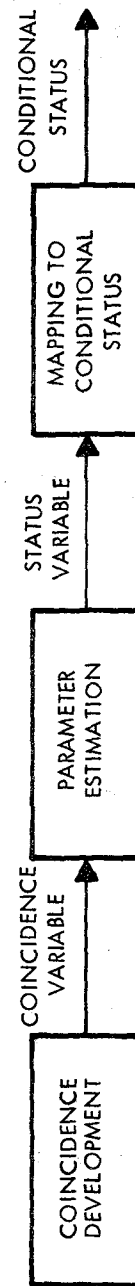


Figure 10

Development has the strongest influence over redundancy design since it is the function which interfaces with the equipment being verified. See Figure 11.

Within the Coincidence Development function, comparisons may be developed in one of three ways; the comparison may be between (or among) the outputs of an equipment being verified, between such an output and a reference, or between the input and output of an equipment being verified. From these three basic methods of comparison, categories for Coincidence Development techniques have been established. These are listed on Figure 12.

In order to provide the information necessary for selecting among the Coincidence Development techniques available, bases for comparison have been developed and appear on Figure 13. Each of the techniques have been investigated with respect to these items.

Realizing the advantages and limitations of each of the techniques, a statement of the applicability of the various techniques has been set forth in the matrix of Figure 14. It may be noted that not only the class of redundancy being verified, but also the type of signal used for verification are important to the selection of a Coincidence Development technique. See Figure 15.

A process for selecting among the Coincidence Development techniques available is shown in Figure 16. The tenant signal is that signal which would exist in the system in the absence of a need for verification; i.e., not a signal injected for verification purposes.

A very simple example of implementing the first three functions of redundancy verification.

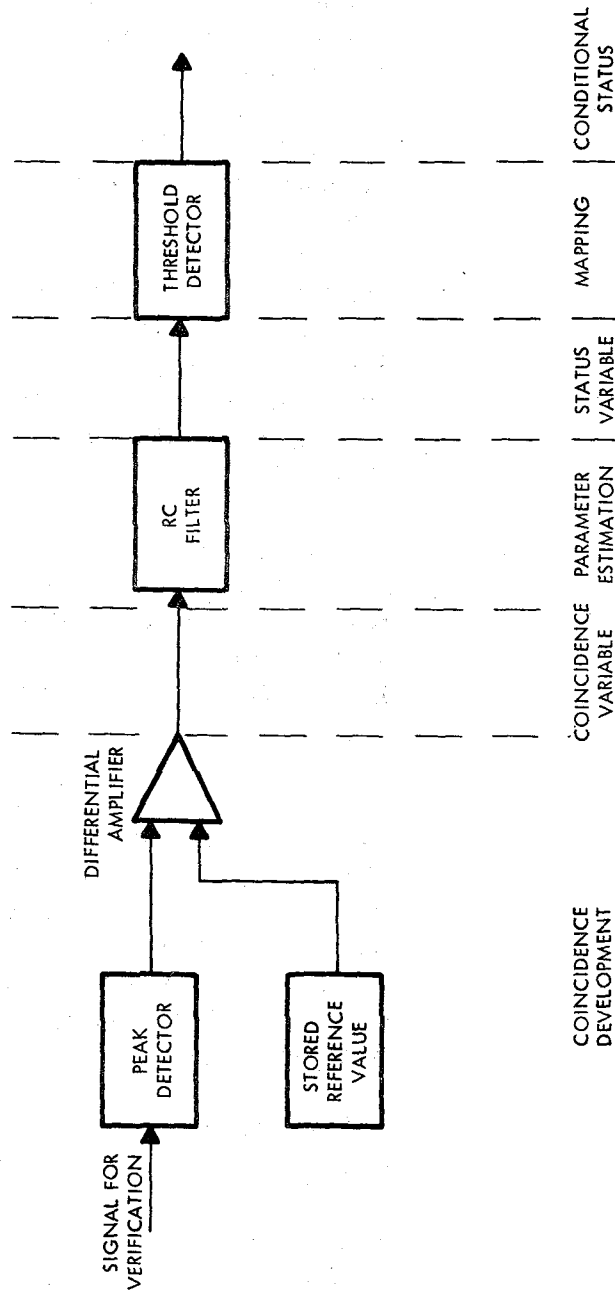


Figure 11

One may form a categorical listing of techniques available to perform the function of Coincidence Development.

COINCIDENCE DEVELOPMENT TECHNIQUES

OUTPUT/OUTPUT COMPARISON

Compare Two (Time)
Voting (Time)
Crosspower Spectral Analysis (Frequency)

OUTPUT/REFERENCE COMPARISON

Value Checks Sequential (Time)
Value Checks Nonsequential (Time)
Coding (Time)
Signal Form Analysis (Time)
Spectral Analysis (Frequency)

OUTPUT/INPUT COMPARISON

Inverse Transform (Time)
Correlation (Frequency)

Figure 12

Failure Types Detectable - Can the technique aid in determining what has gone wrong, or only indicate that something has gone wrong?

Shareability - To what extent must equipment to implement this technique be tailored to the equipment being verified?

Type I & Type II Errors - How prone is this technique to making verification errors?

Assist in Status Resolution - Does the use of this technique decrease requirements on the Status Resolution function?

Complexity - How simple or complex is the implementation of this technique?

Digital Implementation - Is this technique amenable to digital implementation?

Minimum Sampling Rates - What restrictions are placed on minimum sampling rates by the use of this technique?

Unsymmetrical Redundancy - If the redundant elements are not identical, will this influence the use of a given technique?

BASES OF COMPARING COINCIDENCE DEVELOPMENT TECHNIQUES

- | | |
|-------------------------------|----------------------------|
| ● Failure Types Detectable | ● Complexity |
| ● Shareability | ● Digital Implementation |
| ● Type I and Type II Errors | ● Minimum Sampling Rates |
| ● Assist in Status Resolution | ● Unsymmetrical Redundancy |

Figure 13

An applicability matrix has been developed to express ranges of adaptability of the various techniques for Coincidence Development. This adaptability is expressed in terms of the properties of the signal to be used for verification and in terms of the redundancy categories or classes which were established earlier.

APPLICABILITY MATRIX

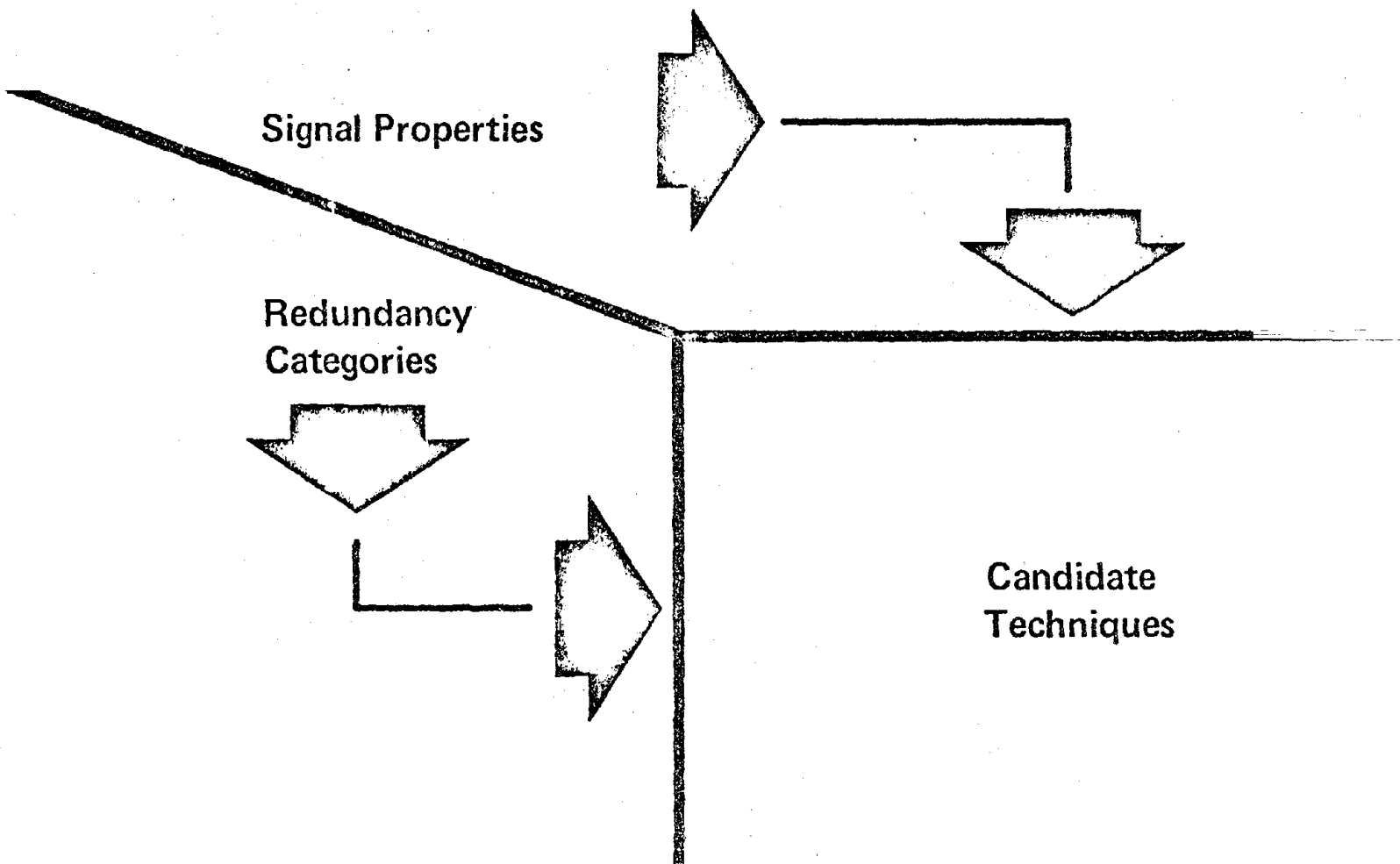


Figure 14

The range of applicability of the various Coincidence Development techniques has been expressed in terms of the redundancy class and the characteristics of the signal to be used for verification.

SIG. PROPERTY CLASS RED CLASS	DETERMINISTIC	STOCHASTIC W/ DETERMINISTIC SYMBIOTIC SIG.	STOCHASTIC STATIONARY	STOCHASTIC NONSTATIONARY	STOCHASTIC NONSTATIONARY W/RANDOM NOISE	INDEPENDENT OF SIGNAL CLASS
A	SP ² VN ² SF ² VS ²	SP ² VN ² SF ² VS ²	SP ² SF ²		SP ² SF ²	CD ² V ³ IT ² CS ³ CR ² CR ³
B	SP ³ VN ³ SF ³ VS ³	SP ³ VN ³ SF ³ VS ³	SP ³ SF ³		SP ³ SF ³	CD ³ V ³ IT ³ CS ³ CR ³ CT ³
C	SP ² VN ² SF ² VS ²	SP ² VN ² SF ² VS ²	SP ² SF ²		SP ² SF ²	CD ² V ³ IT ² A ³ U ³ CT ³ CS ³ CR ²
D	SP ³ VN ³ SF ³ VS ³	SP ³ VN ³ SF ³ VS ³	SP ³ SF ³		SP ³ SF ³	CD ³ V ³ IT ³ A ³ U ³ CT ³ CS ³ CR ³
E	SP ³ VN ³ SF ³ VS ³	SP ³ VN ³ SF ³ VS ³	SP ³ SF ³		SP ³ SF ³	CD ³ V ³ IT ³ CR ³
F	SP ³ VN ³ SF ³ VS ³	SP ³ VN ³ SF ³ VS ³	SP ³ SF ³		SP ³ SF ³	CD ³ V ³ IT ³ A ³ U ³ CR ³
G						IT ¹ CR ¹
H	NOT VERIFIABLE					

IT - INVERSE TRANSFORM
CT - COMPARE TWO
CR - CORRELATION
CD - CODING

V - VOTING METHODS
A - ACKNOWLEDGEMENT
U - USER COMPLAINT
SP - SPECTRAL ANALYSIS

SF - SIGNAL FORM ANALYSIS
VN - VALUE CHECKS; NONSEQUENTIAL
VS - VALUE CHECKS; SEQUENTIAL
CS - CROSS POWER SPECTRUM

1. MAY BE APPLIED ONLY TO SET OUTPUT
2. MAY BE APPLIED TO EITHER SET OR ELEMENT OUTPUT
3. MAY BE APPLIED ONLY TO ELEMENT OUTPUT

A process for the selection of coincidence development techniques has been devised. The required inputs to the design have been defined as have the interfaces between the user and the designer of the verification equipment. The tenant signal is that signal which exists in the equipment being verified in the absence of any requirement for verification; i.e., the signal that would be there anyway.

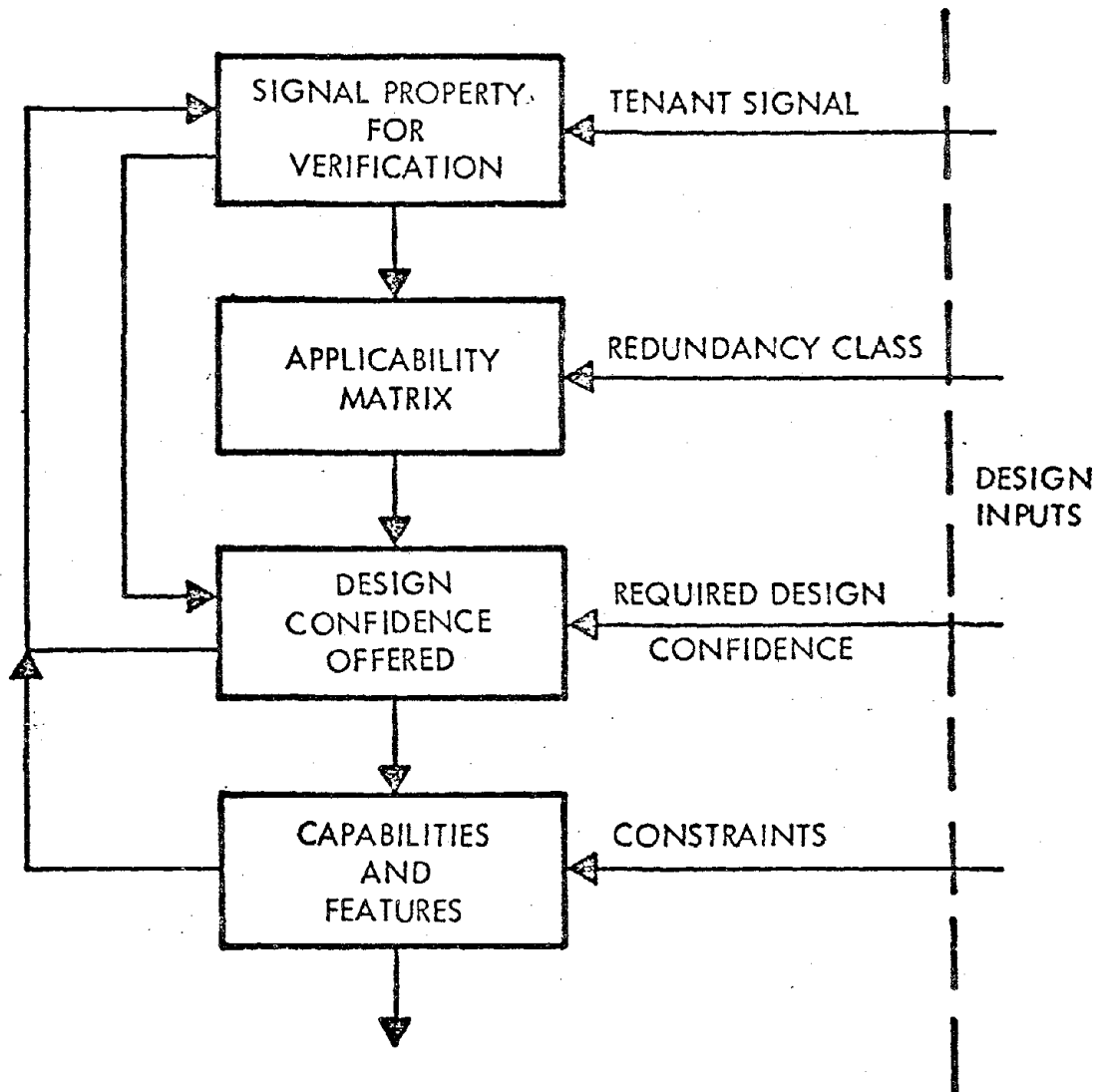


Figure 16

After the Coincidence Development function forms a comparison, and after the results of that comparison are smoothed by the Parameter Estimation function, Mapping to Conditional Status functions as a simple partitioning process. It will often be desirable to use two or more properties of a signal in order to derive a statement of status. This results in a multidimensional status variable, the status variable being the output of the Parameter Estimation function. When the status variable is multidimensioned, it will generally be possible to set up a truth table to translate measurements into a statement of conditional status.

The achievement of continuous verification will frequently be a very difficult task. The question of what degree of mission success is attainable if only periodic verification is employed was addressed. The result is a set of curves, an example of which appears as Figure 17. The likelihood of mission success, $1-\alpha$, appears as a parameter with the time between verifications, T , being a function of the mean time between failures of an element in the redundant set. Results are available for mission success criteria which require one of two, one of three, and two of three (corresponding to the majority voting case) redundant elements to operate successfully.

In summary, this work has resulted in a methodology for the design of redundancy verification; it has provided means for identifying situations which will be unverifiable; see Figure 18, it has resulted in tools, such as the graph of Figure 17, which assist in making the choice between continuous and periodic verification; it has produced design criteria to be imposed on redundant equipment in order to ensure that verification will be possible; and, finally, see Figure 19, it has provided guidance for implementing the previously identified functions of verification.

The question of the degree of success obtainable when only periodic verification is employed has been addressed. Below is a graph relating M_e , the element MTBF and the time between verifications, T .

The parameter $1 - \alpha$, is the probability of mission success. Such graphs have been developed for both two and three-element redundant sets and for majority voting situations.

THREE ELEMENT SIMPLE SETS LINES OF EQUAL PROBABILITY (III)

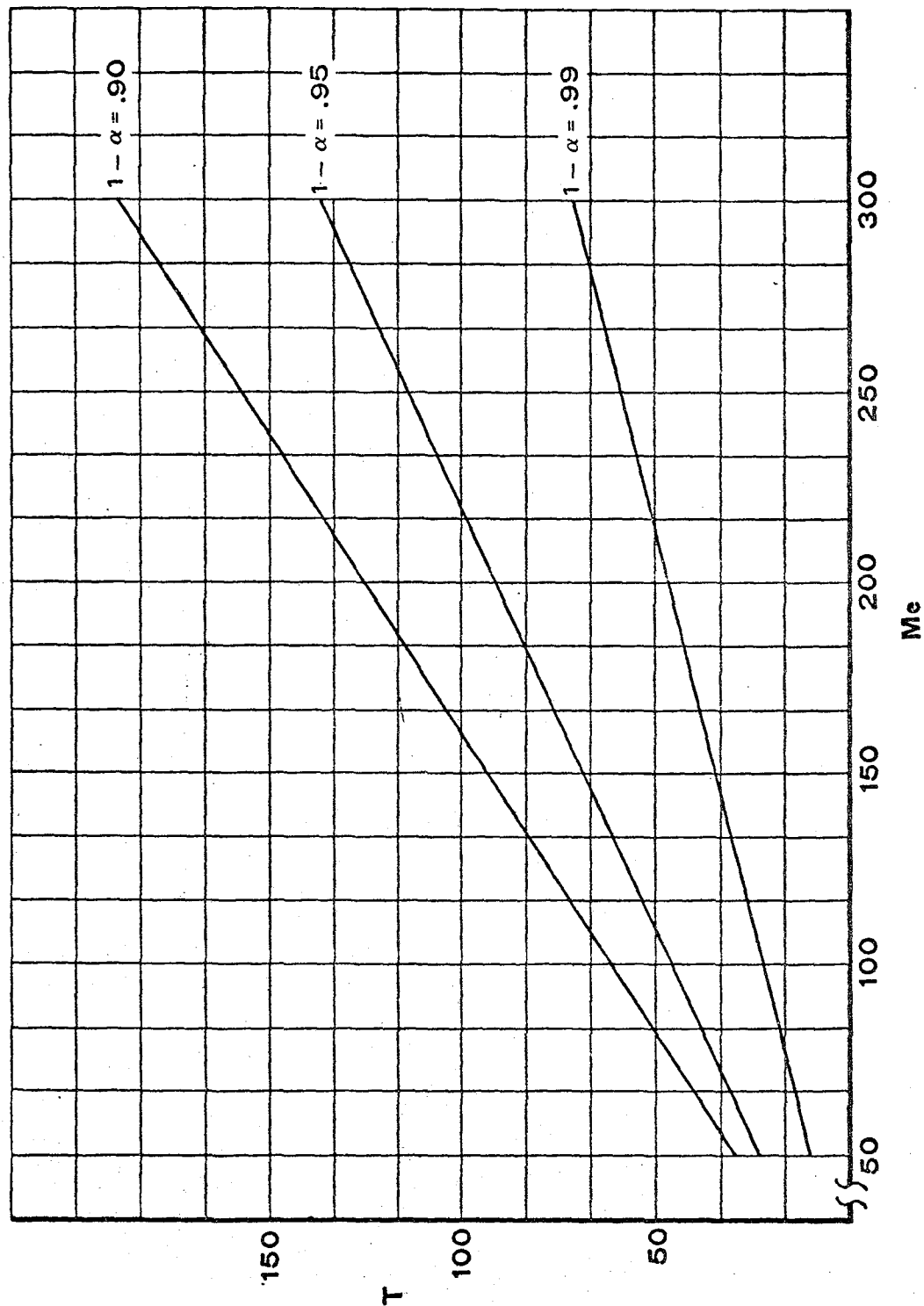


Figure 17

The causes of an unverifiable situation are:

- a) characteristics of the situation place it in redundancy class H.
- b) inaccessibility of the electrical points necessary for verification.
- c) the signal available for verification is not sufficient to establish the desired confidence in the verification.
- d) basic incompatibilities between verification equipment and equipment being verified.

UNVERIFIABLE SITUATIONS


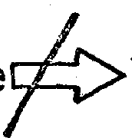
1. Redundant Situation  Class H
2. Electrical Points Inaccessible
3. Signal Available  Verification Confidence
4. Basic Incompatibilities

Figure 18

SUMMARY

- **METHODOLOGY FOR VERIFICATION DEVELOPED**
- **UNVERIFIABLE SITUATIONS IDENTIFIED**
- **AIDS FOR JUSTIFYING CONTINUOUS VERIFICATION**
- **DESIGN CRITERIA DEVELOPED**
- **GUIDANCE FOR IMPLEMENTING VERIFICATION**

Figure 19

SPACE SHUTTLE OPERATIONS ANALYSIS
BY COMPUTER SIMULATIONS

Don G. Satterfield

International Business Machines Corporation

SPACE SHUTTLE OPERATION ANALYSIS

Planning for the Space Shuttle launch operations will be an order of magnitude greater than that required in all previous launch programs.

Optimization of fleet size, facilities and support equipment must be accomplished if cost effective goals of the program are to be met and, indeed, if program launch rates and schedules are to be maintained. Figure 1 lists alternate concepts that must be evaluated over the entire program to determine the most efficient and effective mode of operation.

- o Multiple vehicles will have to be processed in parallel if the high launch rates are to be achieved. On previous launch programs, vehicles have been processed serially.
- o Requirements for a variety of space shuttle missions must be handled efficiently. On the previous launch programs long lead time was available for mission planning. Future space shuttle flight programs must be highly flexible to respond to a variety of new requirements.
- o High launch rates using a fixed fleet size will require short turnaround cycles. A controlled transition must be made from the research and development phase of the program to the fully operational phase.
- o The variety of missions to be flown will contain a number of different payloads. Timely integration of payloads must be accomplished to avoid constraints to the high launch rate.

The use of computer simulations provides an effective method to aid in the optimization of fleet size, facilities and support equipment. It provides a useful tool to test the impact of new requirements as well as evaluate the risks associated with decisions.

SPACE SHUTTLE OPERATION ANALYSIS

- PROCESS MULTIPLE VEHICLES IN PARALLEL
- SHORT TURNAROUND CYCLE
- VARYING MISSION REQUIREMENTS
- MULTIPLE PAYLOAD INTEGRATION
- COST EFFECTIVE

Figure 1

SPACE SHUTTLE OPERATIONS MODEL

The model of a system is the heart of any simulation. The model that is being used for the space shuttle was generated using functional flow diagrams developed during Space Shuttle Phase B studies. Further development of the functional flow (shown) has identified requirements for a number of vehicles, a number of facilities and a number of other support items. Time estimates have to be made to accomplish those tasks identified as requirements to process a vehicle.

The functional flow shows the logic and decision points for each vehicle from launch through landing. See Figure 2. A software model has been developed that contains the same logic. The model reacts to a simulated vehicle in a manner similar to the real system. When launch rates are introduced into the simulation model, data obtained will give insight into the system's behavior.

Significant features of the model include:

- o Learning curves are implemented for each task.
- o Vehicles are serialized for individual investigation.
- o Tasks are worked on two or three shifts, five or seven days a week.
- o Durations of missions are varied to match launch rate model.
- o Operations from first vehicle delivery through total ten-year program are simulated.
- o Reports are tailored to specific area of investigation.
- o Modification of the model is easy.

[illegible]

Figure 2

BASIC MODEL

The basic model (see Figure 3) was exercised to evaluate the system's ability to accomplish the 445 launch mission model. The model was iterated a number of times to establish the required facilities and fleet size. It must be emphasized that the resources tabulated by the model are only as accurate as the estimates of time required to perform individual tasks. Waits for support were encountered in the model flow but none were of such significance as to affect the launch rates. The maximum fleet size utilized during the first year was determined to be three Boosters and four Orbiters.

This exercise demonstrated that the facilities and the number of vehicles identified could support the launch rate. Other data obtained included:

- o Number of flights by each vehicle, by serial number, by year
- o Year and day each flight launched
- o Serial number of booster flown and identification of a specific orbiter
- o Number and average time of waits encountered during each year - reason
- o Average utilization of facility by year.

BASIC MODEL

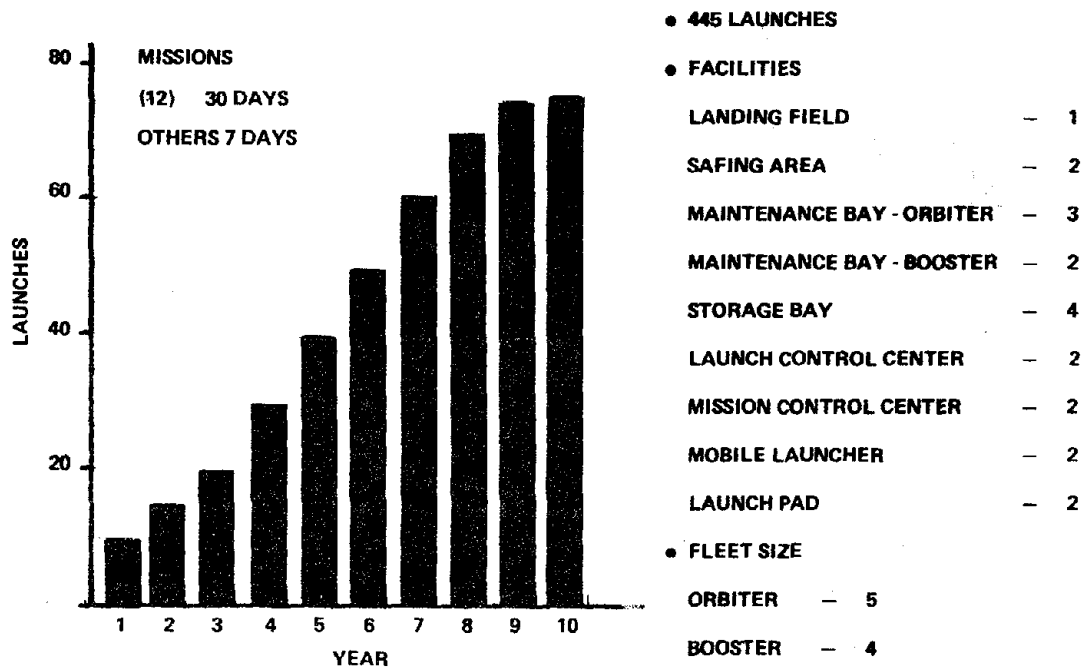


Figure 3

EXAMINE THE IMPACT OF RESCUE REQUIREMENTS

The basic model was modified to examine the impact of rescue requirements, see Figure 4. A test was inserted in each launch process to check if a rescue vehicle would be available for launch in the required time. If a rescue vehicle was not ready within the required time, the prime vehicle was held until the rescue vehicle became available. The test was made just prior to fueling the prime vehicle.

Three conditions were investigated:

- Condition 1 - Rescue launch capability required 32 hours after launch of the prime vehicle.
- Condition 2 - Rescue launch capability required 16 hours after launch of the prime vehicle.
- Condition 3 - Rescue launch capability required 16 hours after launch of prime vehicle. With reduced launch rate, impact of reduced fleet size.

EXAMINE IMPACT OF RESCUE REQUIREMENTS

- **CONDITION 1 — RESCUE LAUNCH CAPABILITY WITHIN 32 HOURS**

4 BOOSTERS - 5 ORBITERS

- **CONDITION 2 — RESCUE LAUNCH CAPABILITY WITHIN 16 HOURS**

4 BOOSTERS - 5 ORBITERS

- **CONDITION 3 — RESCUE LAUNCH CAPABILITY WITHIN 16 HOURS —**
REDUCED FLEET SIZE

3 BOOSTERS - 4 ORBITERS

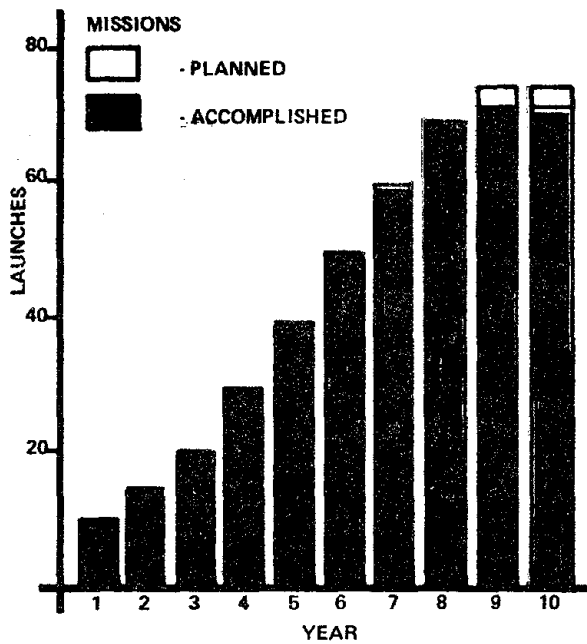
Figure 4

CONDITION 1

The rescue requirement has minimal impact on the number of launches achieved. The mission model was met in every year, except for the 9th and 10th years. The notable impact was in the utilization of the launch pad and the mobile launchers (ML). Waits were encountered for the mobile launchers but total launches achieved were only reduced by five.

A total of 440 launches were achieved. See Figure 5.

CONDITION I



- 440 LAUNCHES

- LAUNCH PAD NO CONSTRAINT

- WAIT ENCOUNTERED FOR MOBILE LAUNCHERS

YEAR	7	8	9	10
NUMBER	21	25	23	22
AVERAGE HOURS	22	37	39	36

- MINIMAL IMPACT ON BASIC MODEL

- FLEET SIZE

ORBITER — 5

BOOSTER — 4

Figure 5

UTILIZATION CHART

Basic and Condition 1

Figure 6 shows the impact of the rescue requirements on the launch pad and the mobile launchers. The early peak is due to a static firing requirement for initial delivery of each vehicle. The high utilization of the mobile launcher indicates that it could be the constraining item in the flow.

FACILITY UTILIZATION

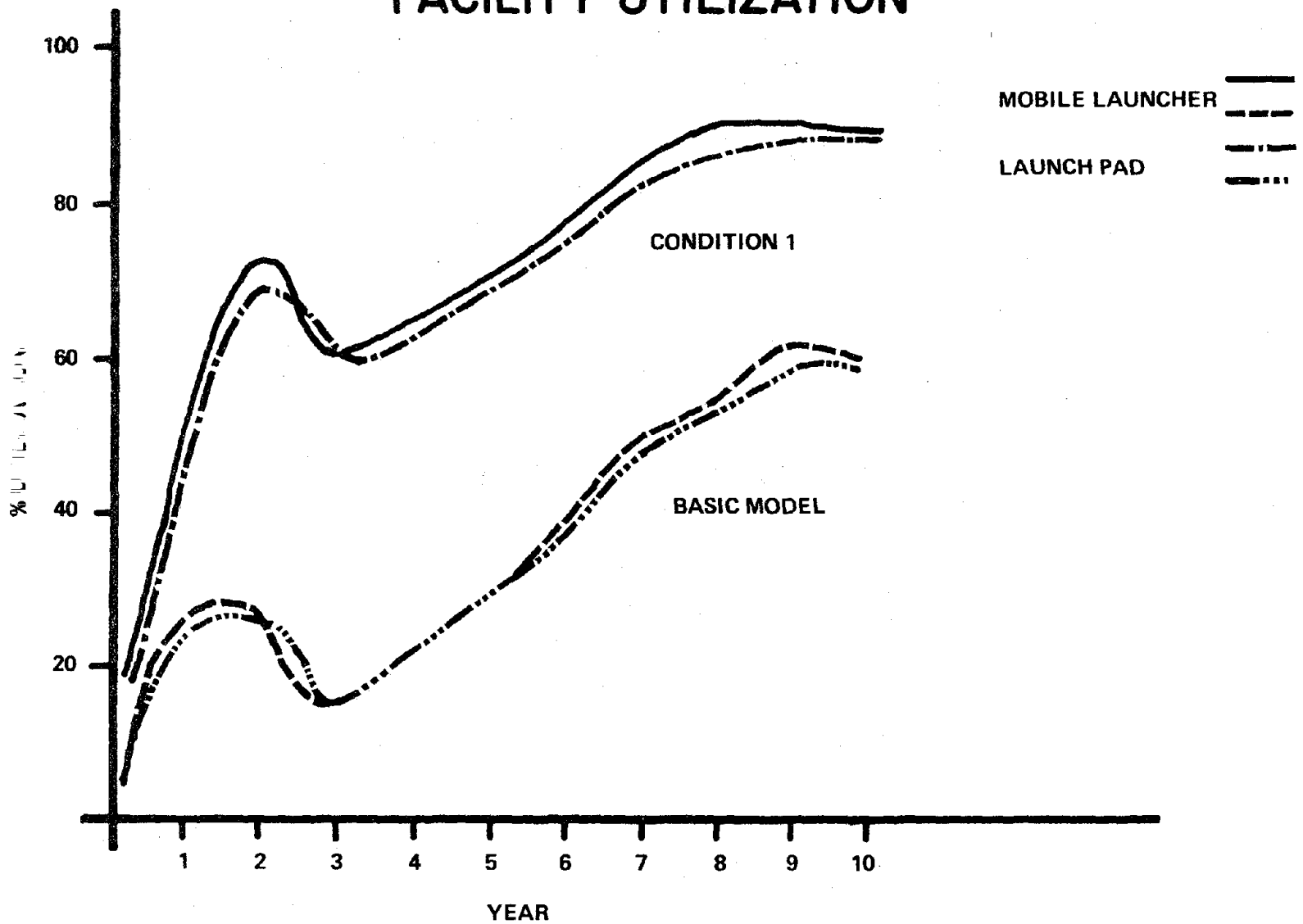


Figure 6

CONDITION 2

The rescue requirement has serious impact on the number of launches achieved. The mission model was met only during the first six years of the program. Numerous waits of long average duration were encountered. These waits resulted in reduced launch rates.

The model was changed to add one mobile launcher, then the model was re-exercised. A total of 421 launches were achieved of the planned 445.

The model was changed to reduce launch pad mobile launcher refurbish time by one day (reduced from five days to four days). The effect was very similar to adding one mobile launcher. Launches achieved numbered 422. See Figure 7.

CONDITION 2

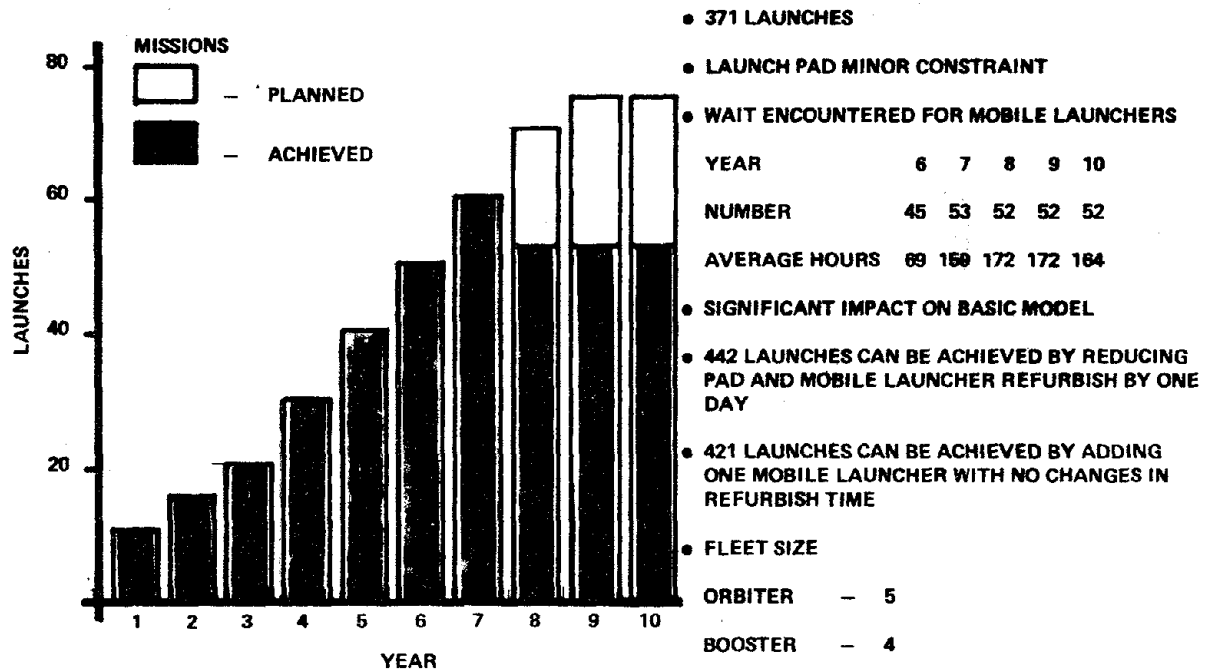


Figure 7

CONDITION 3

The basic model was returned to the original configuration and the fleet size was reduced to three Boosters and four Orbiters.

The model was exercised and 369 launches were achieved.

The conclusion: if the reduced launch rate achieved in Condition 2 is acceptable, reduction of fleet size can be accomplished with minor impact.

This example identifies the importance of re-examining a flow after initial constraints are indicated. See Figure 8.

CONDITION 3

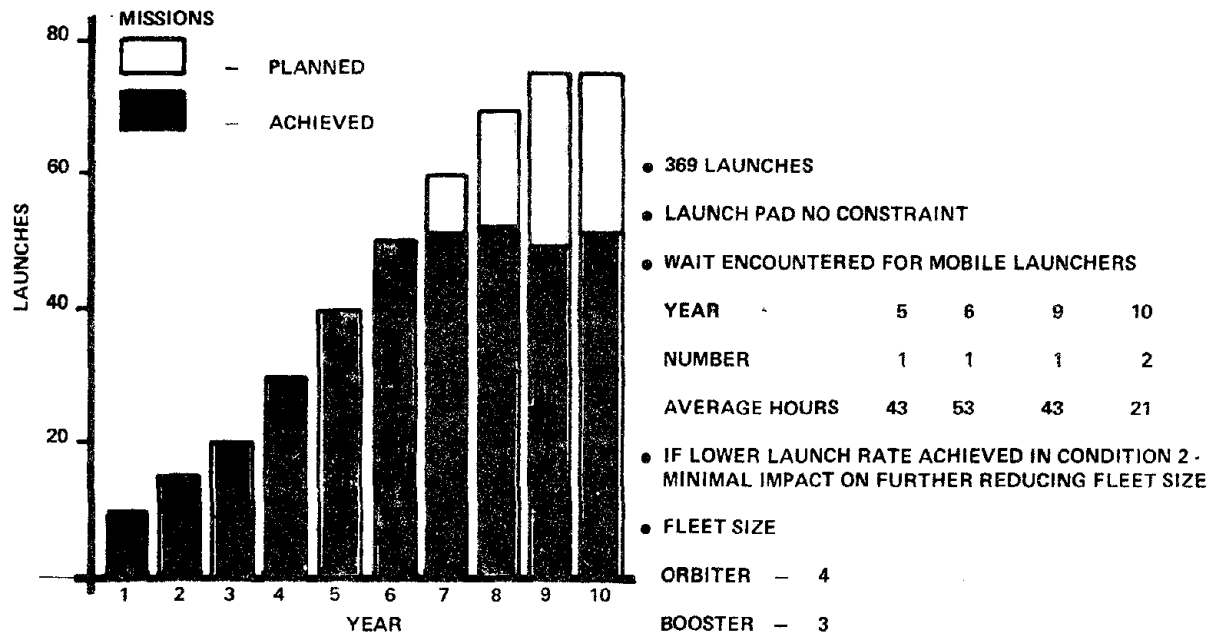


Figure 8

UTILIZATION CHART

Conditions 2 and 3

Figure 9 indicates the constraints preventing achievement of the planned launches. The condition 3 plot indicates that other elements in the flow are constraining launches. The most probable cause is the reduced fleet size for condition 3.

FACILITY UTILIZATION

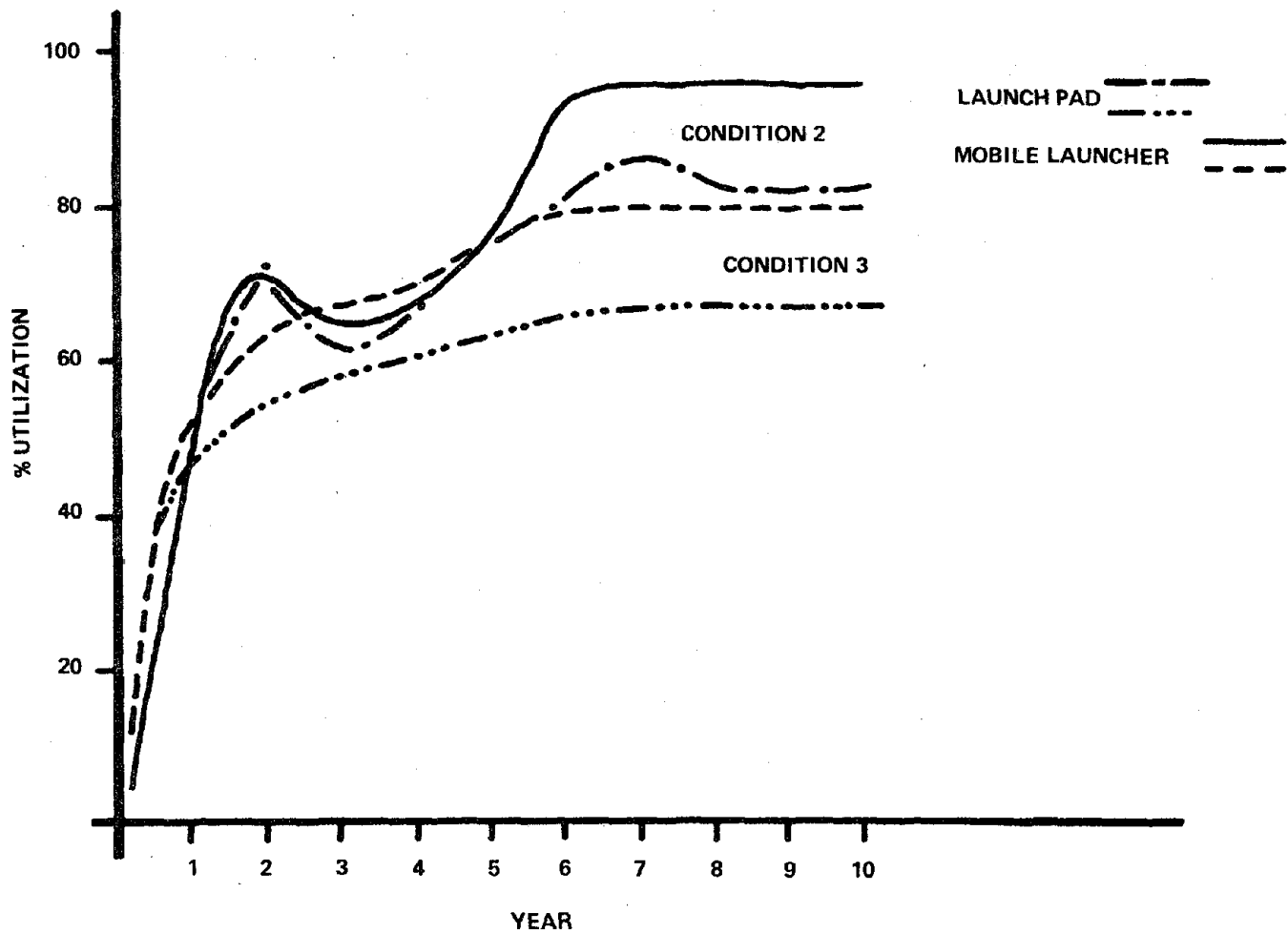


Figure 9

CONCLUSIONS

Computer simulation is a capability that provides an effective means of testing and evaluating proposed operations concepts. The system's behavior is modeled by a computer program which reacts to operating conditions in a manner similar to the planned operational flow of vehicles. Years of operations can be examined in a short time using simulation to gain insight, test hypotheses and the feasibility of alternate concepts.

Computer simulation is not a precise analog of an actual system, therefore, the user must exercise careful judgment in setting up a model and in interpreting the results.

Generating a computer simulation program is a difficult time-consuming task requiring extensive programming experience. To be most effective, a simulation model must be structured for rapid execution and be adaptable to modifications as work proceeds. To avoid extensive development costs, IBM's General Purpose Simulation System (GPSS) has been used to model Space Shuttle launch operations.

It is apparent that detailed data produced by the model will become more meaningful as Space Shuttle program experience is gained. The model can serve as a valuable operational planning tool because of the availability of refined inputs.

It is not suggested that modeling is the solution to all problems, but it is a valuable tool in the study of total program operations. The use of computer simulations will provide insight into program plans and produce data to aid in the decision making process. See Figure 10.

CONCLUSIONS

- **COMPUTER SIMULATION IS A VALUABLE TOOL IN ANALYZING SPACE SHUTTLE OPERATIONS**
- **CARE MUST BE EXERCISED BY THE USER IN SETTING UP THE MODEL AND INTERPRETING RESULTS**
- **GENERAL PURPOSE SIMULATION SYSTEM IS ADAPTABLE TO MODELING THE FLOW OF SPACE SHUTTLE OPERATIONS**
- **THE COMPUTER SIMULATION TECHNIQUE CAN BE APPLIED TO OPERATIONS PLANNING**
- **TOTAL PROGRAM IMPACT CAN BE ASSESSED AS NEW REQUIREMENTS ARE IDENTIFIED**

Figure 10

USING THE COMPUTER AS AN AID IN PLANNING OPERATIONAL ANALYSIS BY SIMULATION

Raul D. Smith

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INTRODUCTION

How can you use a computer as an aid in planning? By providing a means of communicating with it! There are two problems in communicating with a computer, how you talk to it and how it talks to you. How you talk to it is relatively simple - through an interpreter - programmer! How it talks to you is really the problem.

What usually comes out of a computer is a compromise. It depends on the interpretations between the user and the programmer and the programmer and the machine. See Figure 1. And once-in-a-while a keypunch operator throws in an interpretation or two.

COMPUTER APPLICATIONS AND LOGIC

No wonder the computer talks so much and in such strange manners: strange, that is, to a manager. The usual result of this wondrous addition to our brain and fingers is what I jokingly refer to as COMPLOP, communications plopped on your desk to be waded through to find the answer. See Figure 2. The analysis of this COMPLOP is in itself a formidable chore, and, until analyzed, its value is not known.

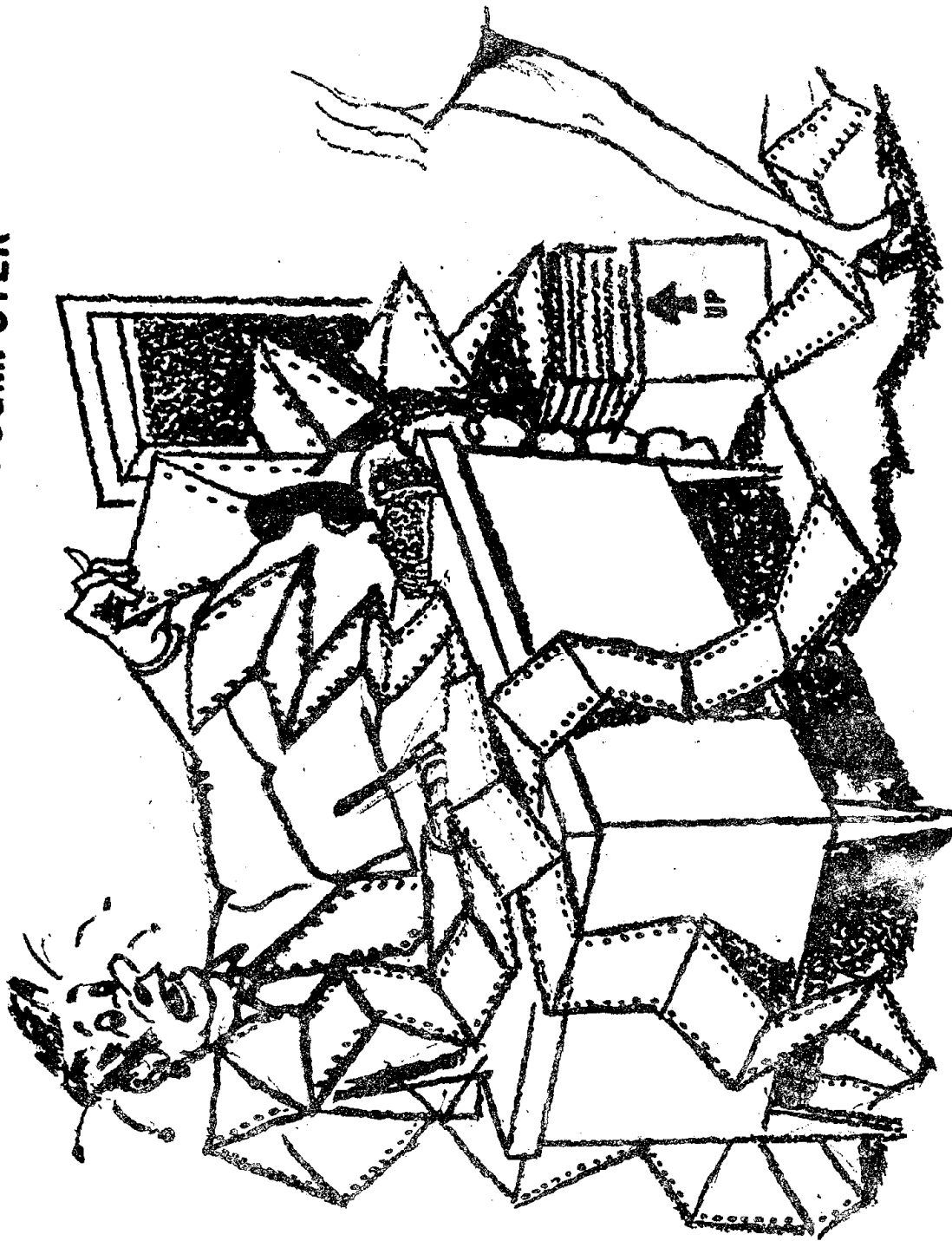
COMPUTER COMMUNICATIONS



NORMAL PATH OF INTERPRETATIONS

Figure 1

COMMUNICATING WITH A COMPUTER



COMPLOP

Figure 2

To circumvent the problem, the obvious answers are (1) do not allow interpretations, (2) let the user make all the decisions, and (3) restrict the machine to calculations and repetitive operations. See Figure 3.

How do you do this? By a graphic display! For planning, what do you want to know? The obvious questions are (1) What, (2) When, (3) How long, (4) How much, (5) What if? See Figure 4. These questions can be related to the simple parameters (1) Nomenclature, (2) Time interval, and (3) Dependency. See Figure 5. These three parameters can be grouped naturally into a flow diagram, see Figure 6, and extended into a waterfall diagram. This is the medium of communications at the Kennedy Space Center. It provides a common basis of communications between all contractors and NASA, and between all levels of operations. The study of the operational support and programmatic effects of a change to this schedule are often time-consuming, complex, and tedious. Considerable effort is expended in manipulating these schedules and answering the questions of (1) How much, and (3) What if?

The logic for this analysis has existed for some time. See Figure 7. Electric circuit design has allowed analysis for some years in determining the effects of a change in the circuit. And notice, the same parameters of nomenclature, time interval, and dependency are present. And also notice the addition of an element in a waterfall is just a change in dependency. See Figure 8.

Many contractors are approaching the requirements of planning using a computer, McDonnell Douglas has ACTNET, IBM has GPSS, and Grumman, GE, and many others have operations models to answer the questions (1) How much and (2) What if?

COMPUTER OUTPUT

PRODUCT OF INTERPRETATION

-- COMPOP - A PROBLEM

ANSWER TO COMPOP

- 1. DO NOT ALLOW INTERPRETATIONS**
- 2. LET USER MAKE ALL DECISIONS**
- 3. RESTRICT MACHINE TO CALCULATIONS**

GRAPHICS - THE ANSWER TO COMPROP

QUESTIONS TO BE ANSWERED IN PLANNING

- 1. WHAT?**
- 2. WHEN?**
- 3. HOW LONG?**
- 4. HOW MUCH?**
- 5. WHAT IF?**

THE BASIC PARAMETERS FOR PLANNING

NOMENCLATURE

WHAT?

TIME INTERVAL

HOW LONG?

DEPENDENCY

WHEN?

Figure 5

XYZXYZXYZ

XYZXYZX

XYZXYXZ

DEPENDENCY

TIME INTERVAL

NOMENCLATURE

time

Figure 6

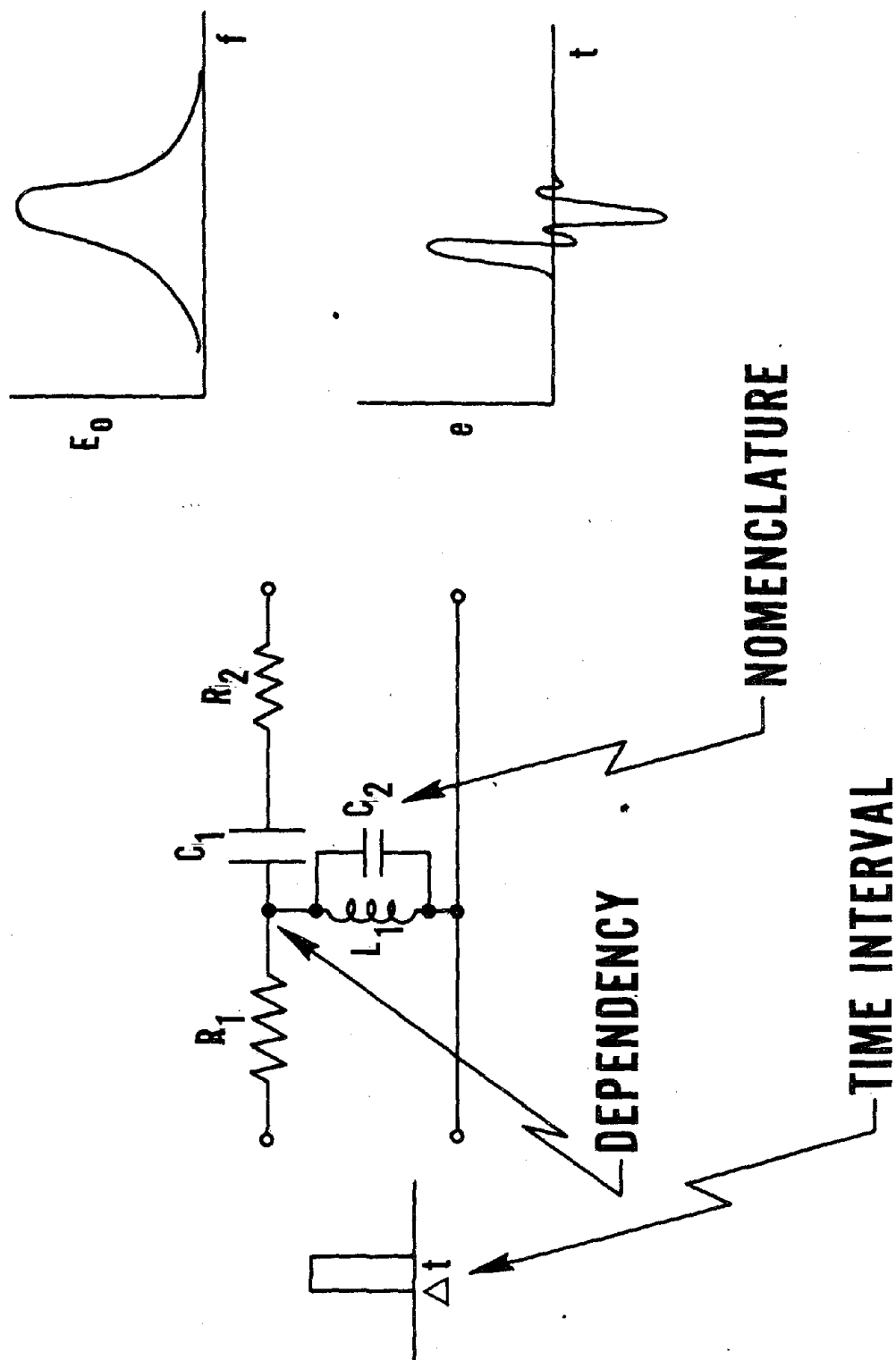
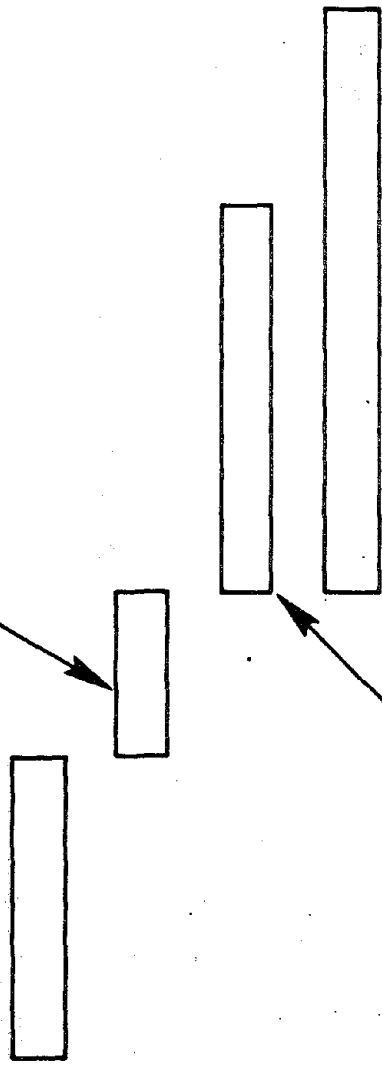


Figure 7

ADDED ELEMENT



CHANGE IN DEPENDENCY

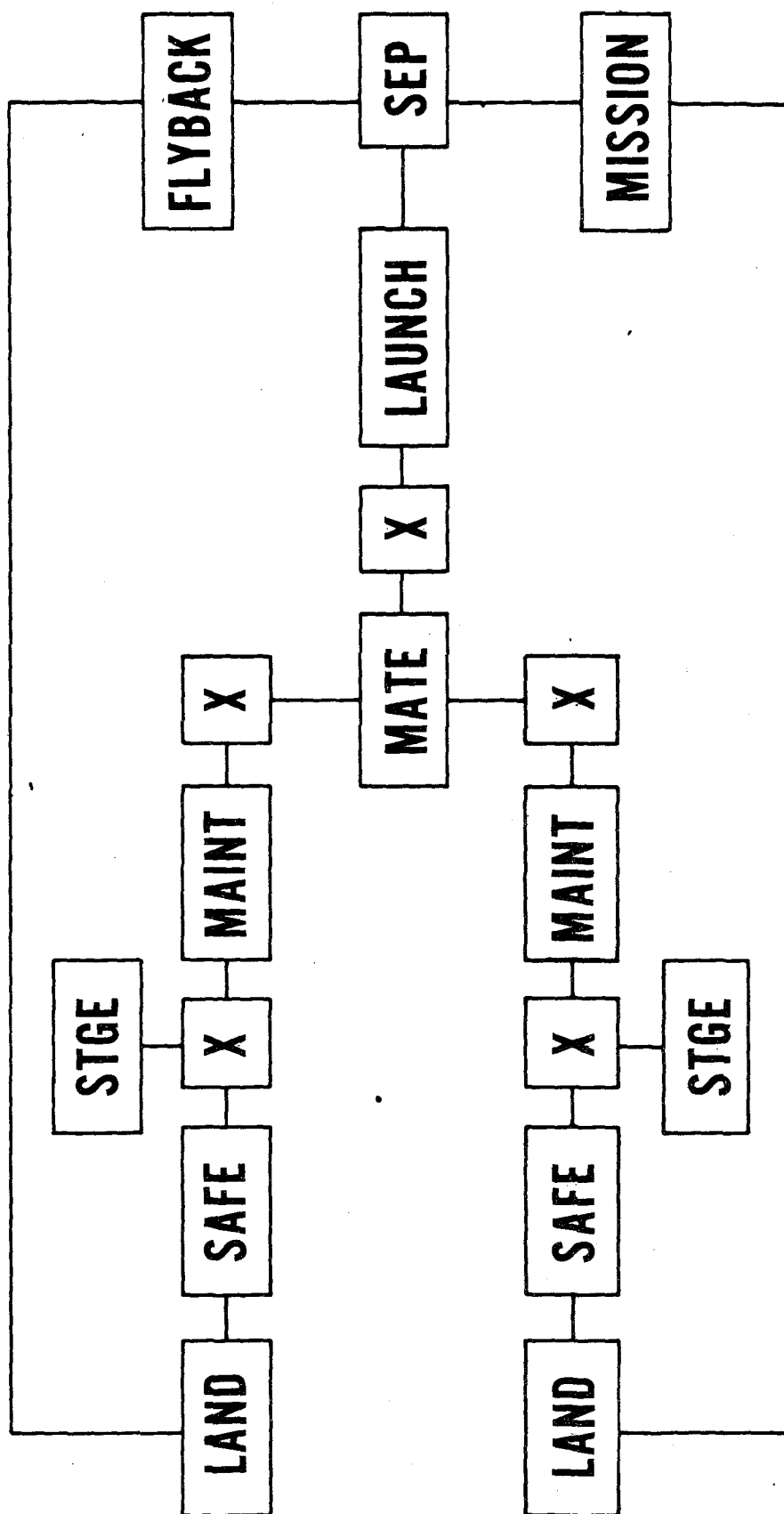
Figure 8

What is stated here is an attempt to put all these programs in perspective with regard to the operations, to show that computer programs need not be tied around data but only the logic of the operations. See Figure 9. Then the logic programs can be applied at any level of operations without a new program being required for each level. This is a significant point, because if the program is not a usable aid for the lowest entity in a program, it is usually not usable at higher levels. Incidentally, taking the data out of the programming will be a cost saving in programming, as many users will understand.

But, let's put the data in! See Figure 10. In a typical operational flow, commodities are associated with each step in the flow. See Figure 11. A data storage and retrieval system, linked with the operational flow can provide summary charts of any commodity we wish to examine under any condition of (1) What if, and (2) How much? Linear or accumulative plots of any commodity can be analyzed when that commodity is summed on the basis of the desired operational waterfall sequence. Similarly, the effects of multiple operations can be analyzed by the same techniques.

COMPUTER PROGRAMS FOR PLANNING

- **BASED ON LOGIC FLOW**
 - **NOT ON DATA**
- **CAN BE APPLIED AT ANY LEVEL OF OPERATIONS**
 - **ACCEPTABLE TO LOWEST,
USABLE BY ALL LEVELS**



(\$, MH. Fac., GSE, gal, etc.)

Figure 10

A1

B1

B2

3

		A		B 1		B 2	
	\$		GSE				
	MH		gal				
			Fac				

COMMODITY FILE

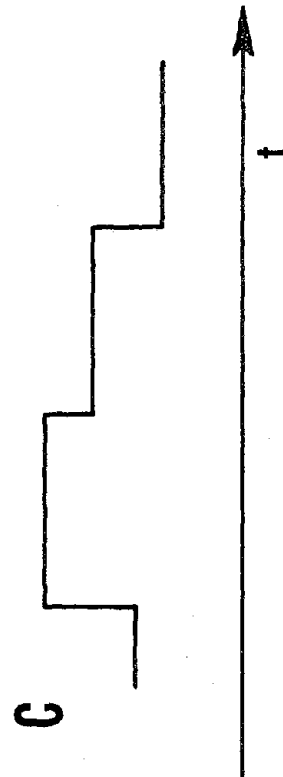


Figure 11

CONCLUDING REMARKS

Without graphic communications, where a picture is worth a thousand words, and a means of relating pictures to real life, and changing the pictures rapidly and economically to reflect real life, computers will have little real use in managerial planning and in actual operations. With this capability, operational and planning personnel will have one of the most powerful tools they could possess. It allows a fast economical analysis of present problems, potential problems, and the avoidance of problems which need not be planned.

Where are we now? We're not there yet! COMPLOP persists! See Figure 12. And the present methods of programming each specific task is costly. But we're not far away, and there are a few points to remember (see Figure 13) when computers and man can really communicate: (1) a computer is no substitute for human reasoning and (2) a human is no substitute for computer capability of repetitive operations, but a tool is no better than the man who uses it.

STATUS

- NOT THERE YET**
- GRAPHICS NOT USED EXTENSIVELY**
- PROGRAMMING BASED ON SPECIFIC DATA IS COSTLY**
- COMPROP PERSISTS**

POINTS TO REMEMBER

- A COMPUTER IS NO SUBSTITUTE FOR HUMAN REASONING
AND DECISION MAKING**
- A HUMAN IS NO SUBSTITUTE FOR COMPUTER CALCULATIONS
AND REPETITIVE OPERATIONS**
- USE A COMPUTER IN PLANNING WITH CAUTION. IT CAN HELP
DEFINE PROBABILITIES, YOU MUST INTERPRET THEM**

FLIGHT OPERATIONS AND SAFETY

DYNAMICS AND CONTROL FOR ORBITAL RETRIEVAL OPERATIONS USING THE SPACE SHUTTLE*

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Abstract

Within the next decade manned space stations will be placed in orbits which already contain large numbers of discarded satellites and other objects. Retrieval or repair of at least some of this refuse is becoming increasingly urgent in order to insure success of many orbital missions and reduce satellite replacement costs. Consideration of technical problems associated with retrieval operations is of timely concern, particularly in view of the current development of an economical space transportation system, the space shuttle. The study discussed in this paper is concerned primarily with dynamics and control problems associated with rendezvous and capture of an uncooperative object. A general discussion of retrieval problems is offered, and problems peculiar to rescue from a tumbling space station are briefly outlined. Specific areas considered with respect to retrieval operations include the problem of despinning an arbitrarily spinning object of moderate size, automatic orbit control for maintaining a given parking position relative to an object, transfer trajectories of a despin package, and techniques for determining spin axis and rate of an uncooperative body.

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Introduction

Over the past 13 years mankind has placed in excess of 4,800 objects into earth, lunar, and solar orbits.¹ At least 2,100 of these are still in orbit, most of which are circling the earth. There are only a few hundred satellites among this number, with the remainder consisting of launch vehicle upper stages, payload fairings, and other components related to insertion of satellites. Although the average number density of these objects is negligible, most are confined to just a few popular orbits, e.g., synchronous and low, inclined orbits. Large space stations will be placed in some of these orbits, while the probability of collision is continuously increasing due to further addition of satellites and launch vehicle components. Retrieval or repair of at least some of this discarded matter is becoming an urgent concern with regard to the success of many future orbital missions.

The high cost of satellite replacement offers another incentive to develop retrieval and repair capabilities. Since use of the space shuttle is assumed for such operations, repairs could be carried out once the satellite is captured and secured by the shuttle. After renovation it could be returned to useful service. An alternative to in-orbit repair of a spent satellite is to deliver a replacement spacecraft and retrieve the damaged one for later repairs and return to orbit.

An additional objective of space retrieval operations might be the return to earth of satellites particularly important to scientists and curators. Much can be learned from satellites exposed to the space environment for long periods of time. Furthermore, there is a great deal of prestige associated with retrieving some of our early spacecraft.

A considerable amount of work has been done in the areas of space rescue, satellite inspection, rendezvous techniques, and space shuttle technology. However, several unique problems associated with rendezvous and docking with an uncooperative object have not been considered elsewhere. Of particular interest is the problem of despinning an uncooperative object of moderate size and arbitrary shape, which possesses an unknown spin rate about its major principal axis. A preliminary design of a remotely operated despin package is presented. Its configuration, dynamics,

and control systems are discussed in detail. Other problem areas considered in this paper include object detection and identification techniques, spin rate and axis orientation determination methods, automatic stand-off control for maintaining a given position relative to an object, and transfer maneuvers between shuttle and object. In addition, a general discussion of retrieval operations is presented.

Operational Aspects of Retrieval

This study is concerned primarily with the retrieval of unmanned, uncooperative objects of moderate size, e.g., weather and other scientific data collecting satellites whose operation has terminated due to any of several causes. Table 1 lists several possible candidates for retrieval. These satellites, and other objects, do not incorporate docking provisions, and, in fact, are likely to be spinning due to propellant leakage, valve or gyro failure, or initial dynamic state. It is assumed, however, that objects to be retrieved are spinning in a stable mode about their respective major principal axes of inertia. This is the state attained after a period of time in which kinetic energy is being dissipated by liquid sloshing, elastic deformation of structural members, or nutation dampers. For objects of the size considered here, the time required to reach a stable state is, at most, of the order of weeks, after significant attitude disturbances have stopped. However, large objects such as space stations which are tumbling, may require several months to passively dissipate enough energy in order to reach a stable spin state about the major principal axis. Techniques presented here would not be directly applicable to rescue from such a space station, primarily because tumbling motion does not have an inertially oriented spin axis associated with it, which is assumed in the work reported here.

Since the most economical means of reaching an object in a low orbit for retrieval, repair, or elimination will be by using the space shuttle, many aspects of the operational sequence assume a man will be controlling the events and maneuvers. Automatic control systems are assumed whenever practical, but the nature of such missions requires the ability of a man to make decisions and perform functions which are prohibitive in an automated mode, because of the inherent uncertainties involved. Missions to high altitude orbits would require very

similar maneuvers. However, shuttle performance is expected to limit it to low altitude orbital missions. Nevertheless, the state of knowledge is assumed to be compatible with retrieval missions in the time period of interest.

The initial task in a retrieval sequence is considered to be locating and identifying the object upon arrival in its predetermined vicinity. The size and shape of the search area will greatly influence the method of search and identification, and time to search. Furthermore, a successful rendezvous requires great accuracy in orbit determination. A non-cooperative radar rendezvous system for the space station program, which may also be of value to object retrieval and rescue missions, has been proposed by industry, e.g., Westinghouse.² It is understood that the accuracy of orbit determination by ground tracking will permit the shuttle to be guided very close to the target object. In fact, the search region within which the target is predicted to be located is a cone with a four mile diameter, five miles long (1σ), up to a possible 12 mile diameter, 15 miles long (3σ), with the shuttle at the apex.³ The system offered, by Westinghouse for example, has a range of at least 30nm with range accuracy of about 1 percent and angular accuracy of 2 milliradians (3σ). Once in the search cone the system can automatically scan the region and detect an object in about a minute.

One possible method of identification upon initial acquisition of an object employs a television camera guided by the radar tracking system. A zoom lens can be used to receive an image with limited resolution. If the object is spinning a "frozen" scene television display can be produced. This is equivalent to using a mechanical strobe, except the picture is "flashed" on a storage tube. The image can be held up to about 2 minutes or reinforced at the spin rate of the object. However, the degree of resolution is somewhat uncertain with such a system. To determine the dynamic state and physical condition of a spinning body with assured accuracy and image quality, an optical or electronic strobe is very effective once the shuttle is within a few hundred feet of the target.

After locating and identifying the object, orbital maneuvers are executed to approach and acquire a stand-off position relative to the target. If the object is not spinning or has some minimal spin rate and is of acceptable size, a direct docking may be attempted. Otherwise, the shuttle must maintain a stand-off or

parking position while the despin package is deployed to eliminate angular momentum. Objects which are too large for retrieval are not considered here. However, there are relatively few such items, because their orbits tend to decay rapidly due to pronounced drag effects.

Rendezvous maneuvers, which are considered to be standard,⁴ are anticipated during approach of the shuttle to the stand-off position. Upon arriving at this position an autopilot will be enlisted to maintain the spatial relationship with the target while the attitude control system maintains proper orientation. Assuming a despin maneuver is required, the despin package must make an orbital transfer from the shuttle to a position close to the object. The optimum position is one in which the axis of the package is in line with that of the object spin axis. Fine adjustments are to be made after one of the shuttle crewmen checks alignment via remote television cameras on the package.

Actual attachment to and despin of the object is carried out by a ring which is aligned with the object spin axis. This ring is spun up to the same angular speed as the target, while the main body of the despin package remains 3-axis oriented in an inertial frame. After the ring is synchronized through the use of a television camera, it is translated along its axis with the main body until a position near the center of mass of the object is reached. At that point attachment arms are extended from the ring toward its center. Once the target is secured by these arms, despin is executed with momentum being dumped via attitude jets on the main body of the package. A docking device on this inertially oriented body allows the shuttle to rendezvous and recapture the package with object in hand, and stow it in the cargo bay for return or repair.

In many cases it is desirable to eliminate a piece of space junk without carrying it in the shuttle. To accomplish this a remotely fired retro-pack could be attached to an object after despinning. Of course, this device would reentry with the object and would not be reusable.

Despin Package Transfer Trajectories

Although the actual transfer of the despin package from shuttle to object may require several impulses and corrections, an ideal transfer might be one in which only two impulses are applied, one upon leaving the shuttle position and one to eliminate relative closing velocity at the object. Thrust computations are performed in a moving coordinate frame with origin at the target, as illustrated in Figure 1. The x-axis is positive along the direction of motion, y-axis is normal to the orbital plane, and z-axis is along the local vertical, in accordance with Project Apollo Standards.⁵ Equations of motion for a transfer trajectory to an object in a nearly circular orbit are well-known.⁶ In the moving x, y, z frame, for thrust-free transfer, these equations are

$$\left. \begin{aligned} \ddot{x} + 2n\dot{z} &= 0 \\ \ddot{y} + n^2 y &= 0 \\ \ddot{z} - 2n\dot{x} - 3n^2 z &= 0 \end{aligned} \right\} \quad (1)$$

where $n = (GM_E/a^3)^{1/2}$, the mean motion of the target in its orbit. For orbits of interest here,

$$n \sim 10^{-3} \text{ rad/sec.}$$

The solution of set (1) is readily obtained in closed form:

$$\left. \begin{aligned} x(t) &= \frac{2\dot{z}_0}{n} \cos nt + \left(\frac{4\dot{x}_0}{n} + 6z_0\right) \sin nt + \left(x_0 - \frac{2\dot{z}_0}{n}\right) - (3\dot{x}_0 + 6nz_0)t \\ y(t) &= y_0 \cos nt + \frac{\dot{y}_0}{n} \sin nt \\ z(t) &= \frac{\dot{z}_0}{n} \sin nt - \left(\frac{2\dot{x}_0}{n} + 3z_0\right) \cos nt + \left(\frac{2\dot{x}_0}{n} + 4z_0\right) \end{aligned} \right\} \quad (2)$$

Of course, the out-of-plane y- component results in simple harmonic motion. Since the shuttle is assumed to be in the object orbit plane, this component of motion is initially zero, and remains so for the transfer. The despin package will

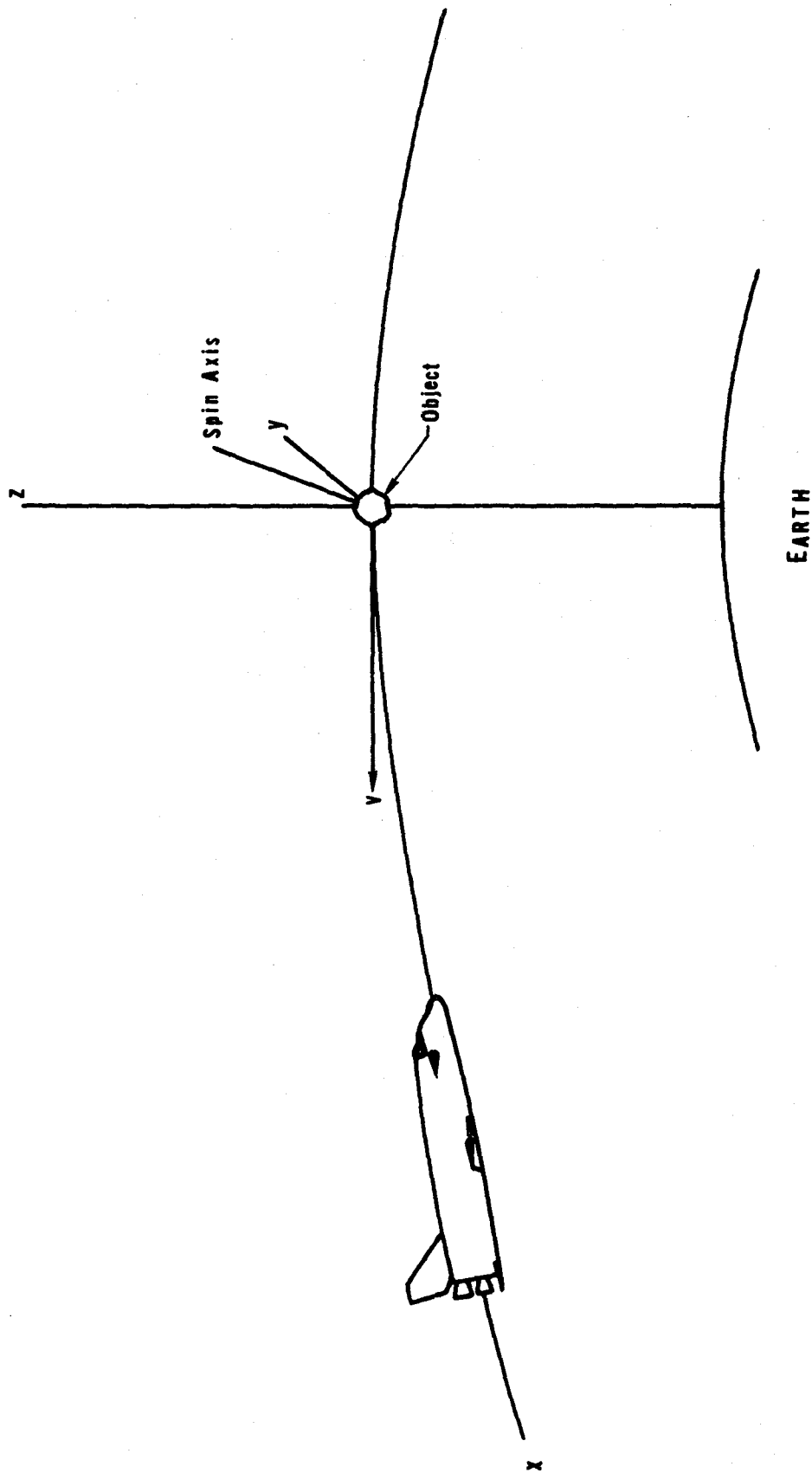


Figure 1. Shuttle/Object Relative Position Nomenclature

generally have to perform a terminal maneuver taking it out of the original orbit plane for alignment with the object spin axis.

In-plane transfer motion is coupled between x- and z-components. Although this is stated as an initial value problem, the only acceptable values of initial conditions x_0 , z_0 , \dot{x}_0 , and \dot{z}_0 are those which result in x and z simultaneously approaching zero at some reasonable time after leaving the shuttle. Values of \dot{x} and \dot{z} at that time represent the closing velocity between despin package and object, and a thrust maneuver is required to avoid collision and establish a parking position along the spin axis of the target and very close to it.

Since solution set (2) is linear in initial velocity components, the required values of these components can easily be well approximated as functions of x_0 , z_0 , and t by setting $x = z = 0$ and solving for \dot{x}_0 and \dot{z}_0 . As a further simplification, the shuttle is assumed to be positioned on the x-axis. Then $z_0 = 0$, and initial velocity components are given as

$$\dot{x}_0 = \frac{-nx_0 \sin nt}{8(1 - \cos nt) - 3nt \sin nt}$$

$$\dot{z}_0 = \frac{2nx_0 (1 - \cos nt)}{8(1 - \cos nt) - 3nt \sin nt}$$

These resulting expressions indicate that initial relative velocity requirements for the despin package transfer are functions of x_0 and time of transfer, t. For example, if the object is in a circular 200 km orbit with the shuttle positioned 100 ft. ahead of it, in order to transfer the package in 15 minutes the initial velocity components must be

$$\dot{x}_0 = -0.068 \text{ fps}$$

$$\dot{z}_0 = 0.100 \text{ fps}$$

The transfer trajectory for this case is plotted in Figure 2. The shape of this path is typical of such transfers. Closing velocity components are obtained by differentiating the position expressions, set (2) and evaluating \dot{x} and \dot{z} at the value of t corresponding to the transfer.

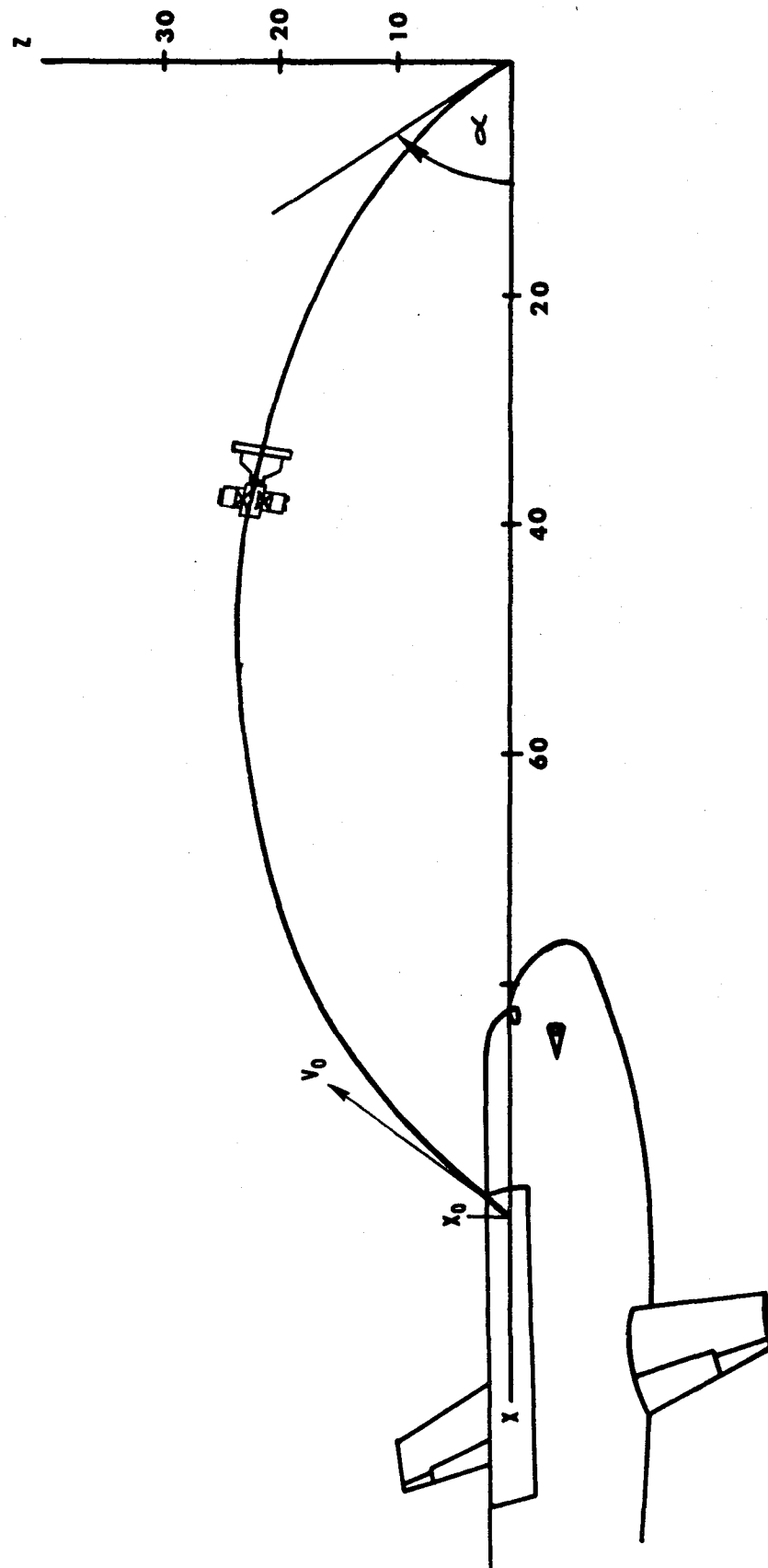


Figure 2. Example Transfer Trajectory of Despin Package

The final approach angle α should correspond to the projection of the object spin axis onto the orbit plane. Then a final out-of-plane maneuver by the despin package will permit final alignment. For given shuttle stand-off position, this angle is only a function of transfer time. The computer required to make transfer calculations and generate commands can be housed in the shuttle and a data link used to control the despin package maneuvers.

Shuttle Stand-Off Autopilot

As previously discussed, the shuttle will be required to maintain a fixed relative position with respect to the target during despin operations. It is assumed that an automatic system will be used to control a position in the target orbit plane at an (x, z) location, as shown in Figure 1. Continuous range, range rate, and angle data may be provided by the tracking radar system. This information in combination with an inertial navigation system can be transformed to the $x, y, z, \dot{x}, \dot{y}, \dot{z}$ format and used by the autopilot to generate commands for the orbit control system.

Automatic position control can be modelled by using the non-homogeneous form of equations (1),⁶

$$\left. \begin{aligned} \ddot{x} + 2n\dot{z} &= f_x \\ \ddot{y} + n^2 y &= f_y \\ \ddot{z} - 2n\dot{x} - 3n^2 z &= f_z \end{aligned} \right\} \quad (3)$$

where f_x, f_y, f_z are the applied acceleration components, including both disturbance and control forces. As an example of control system synthesis, consider the simplified situation in which z_0 is zero, as illustrated in Figure 1.

This assumption leads to homogeneous initial conditions, and a valid transfer function, by defining a new coordinate,

$$\lambda = x_0 - x$$

Initial conditions associated with set (3) become

$$\lambda(0) = \lambda_0 = 0, y(0) = y_0 = 0, z(0) = z_0 = 0$$

$$\dot{\lambda}(0) = \dot{\lambda}_0 = 0, \dot{y}(0) = \dot{y}_0 = 0, \dot{z}(0) = \dot{z}_0 = 0$$

taking the Laplace transform of the differential equations and solving for $\Lambda(s)$, $Y(s)$, $Z(s)$ gives

$$\begin{aligned}\Lambda(s) &= \frac{s^2 - 3n^2}{s^2(s^2 + n^2)} F_x(s) - \frac{2n}{s(s^2 + n^2)} F_z(s) \\ Y(s) &= \frac{1}{s^2 + n^2} F_y(s) \\ Z(s) &= \frac{1}{s^2 + n^2} F_z(s) + \frac{2n}{s(s^2 + n^2)} F_x(s)\end{aligned}\tag{4}$$

The control law assumed for this application implies the use of continuously variable thrusters. Since feedback is available from the tracking system on position and velocity, the control forces may be of the form

$$f_{cx} = -K_x (\dot{\lambda} - K_1 \lambda)$$

$$f_{cy} = -K_y (\dot{y} - K_2 y)$$

$$f_{cz} = -K_z (\dot{z} - K_3 z)$$

where λ , y , z and $\dot{\lambda}$, \dot{y} , \dot{z} are position and velocity errors, respectively. Negative signs in the brackets assure negative feedback. Of course, the reference values, λ_c , y_c , z_c , $\dot{\lambda}_c$, \dot{y}_c , \dot{z}_c are all nominally zero for this control situation.

Figures 3 and 4 illustrate the block diagrams for the three components. Note that λ - and z - components are coupled, as is evident from equations (3). To determine the system transfer functions, each input is taken separately. The y - component is uncoupled and has inner loop transfer functions

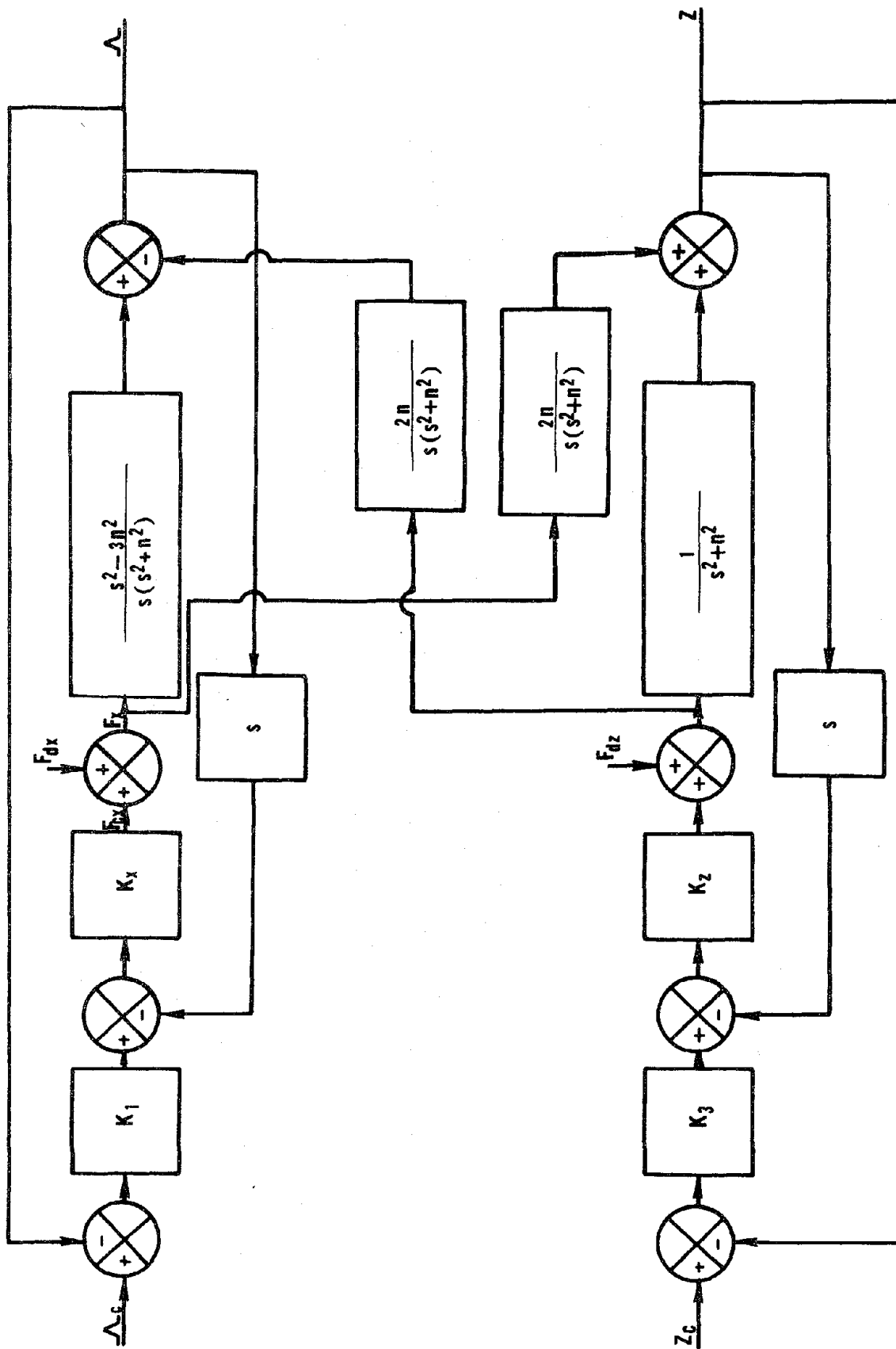


Figure 3. Block Diagram of Δ , Z Coupled Position Control

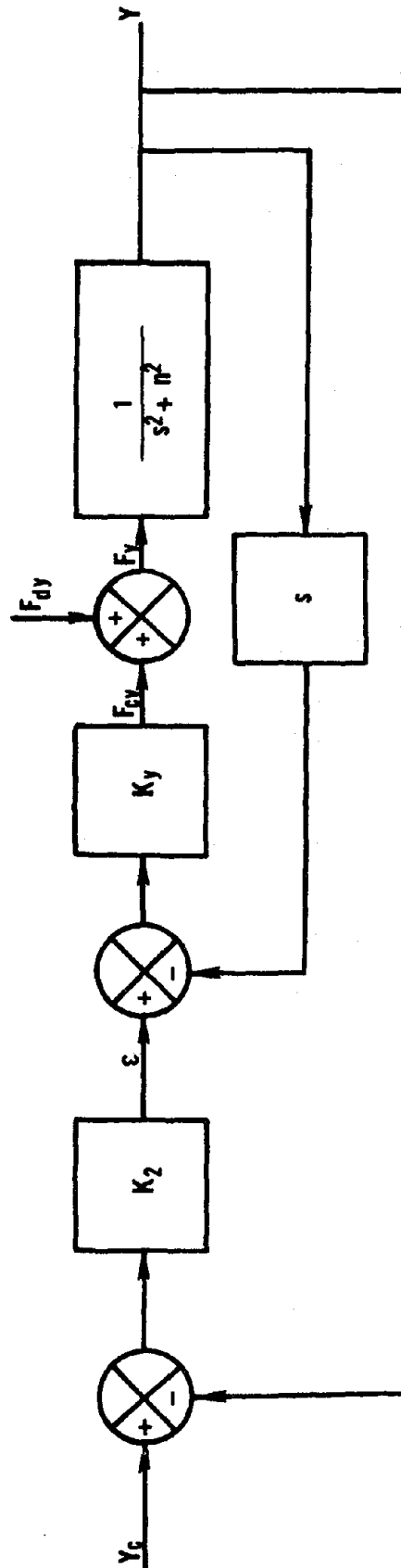


Figure 4. Block Diagram of Y-Component Position Control

$$\frac{Y}{\epsilon} = \frac{K_y}{s^2 + K_y s + n^2}$$

$$\frac{Y}{F_{dy}} = \frac{1}{s^2 + K_y s + n^2}$$

and outer loop transfer functions

$$\frac{Y}{Y_c} = \frac{K_y K_2}{s^2 + K_y s + (K_y K_2 + n^2)}$$

$$\frac{Y}{F_{dy}} = \frac{1}{s^2 + K_y s + (K_y K_2 + n^2)}$$

where F_{dy} represents the y- component of disturbance force.

The two coupled components represent a more difficult situation. Since the gain of the coupling term is of the order of the mean motion n , it is easily seen that the coupling has relatively little effect on the component systems, because the value of n is so low. Therefore, the coupling term will be neglected for the moment. An analog simulation was used to verify the validity of this assumption.

The λ - component function in relations (4) is also complicated by the two zeros in the numerator of the system equation. Again considering the magnitude of the mean motion, an approximation can be made by canceling the $s^2 - 3n^2$ term with s^2 in the denominator. These simplifications result in a system consisting of three identical and independent components. Therefore, an analysis of one component is also valid for the other two.

Steady state errors of the system are found by applying the final value theorem. For a step input of unity, the steady state errors in the command signal are unity, and the steady state errors in x,y,z disturbances are $(\frac{1}{K_1 K_x})$, $(\frac{1}{K_2 K_y})$, and $(\frac{1}{K_3 K_z})$, respectively. Thus, as amplifier gains are increased these disturbance errors decrease.

The root locus method was used to establish stability criteria and determine required compensations. Coupling effects were neglected for the stability analysis. Since coupling is so small, stability should not be effected. For the y- component, the innerloop pole-zero plot consists of two poles symmetrically located on the imaginary axis. As the gain is increased with negative feedback the locus loops down to the left half of the real axis. Since the pole locations correspond to the dimension of the mean motion, low frequency and high damping result even at low gains. A high gain will improve the response in the total system (outer) loop, giving two poles on the real axis, one at zero and the other at the value of K_y in the left-half plane. With negative feedback in the outerloop this locus will have two vertical asymptotes breaking away from the real axis at the point corresponding to half the value of K_y . Therefore, by varying both K_y and K_2 , the root locus can be positioned as desired in the left-half plane. Selection of exact values will depend on required response characteristics.

Since approximations involving the mean motion and coupling effects between x- and z- components resulted in identical transfer functions for all three components, the stability analysis for each is identical to that of the y- component. Validity of ignoring this coupling on stability can be demonstrated qualitatively. The original transfer function, including coupling and mean motion terms, indicates four poles and two zeros in the vicinity of the origin. One zero is in the right-half plane; implying probable instability of the system. The difficulty in compensating this zero may be excessive. However, the associated frequency of instability is of the order of the mean motion, i.e., one cycle per orbit. The total system frequency should be several orders of magnitude greater than this, indicating that the system will respond long before an instability can reach a significant value.

The control system can now be designed to meet the required response criteria. By proper selection of gains the desired combination of damping ratio, overshoot, and natural frequency can be achieved. Since each component is represented by a second order system, natural frequency and damping ratio are obtainable directly from the location of the poles on the corresponding root locus diagram.⁷

An analog simulation of system response was made in order to check validity of approximations made in the analysis and obtain response curves for all three components. The analog program was developed by substituting values for gain constants into the differential equations. These values were chosen such that the damping ratio would be about 0.8 and the natural frequency about 30 rad/sec. This led to an innerloop gain of 51.2 and outerloop gain of 20.0. Single y-component system response in both position and velocity was found for unit step and impulsive inputs, as shown in Figure 5. Inputs are either command signals or disturbance forces. Significance of the mean motion magnitude on response was, in fact, found to be negligible for these operating conditions. Thus, responses of the y-component system represent all three systems.

From these considerations it seems possible to use three simple control systems to maintain the relative position of an orbiting vehicle with respect to another object. Since each system is a simple second order type, it has excellent stability characteristics.

Spin Axis and Rate Determination

As mentioned previously, it will be necessary to determine the spin axis orientation and angular rate of a passive object before capture by the space shuttle. There are several techniques which might be useful for spin determination. Two are considered here, one method which has already been briefly discussed employs a television "frozen" scene display. The other method makes use of a mechanical strobe developed by E. T. Pearson of the Frankford Arsenal⁸. This device utilizes two counter rotating prisms to produce a fixed image when the prism speed is synchronized with the object spin rate. The method is shown schematically in Figure 6. A calibrated drive motor control can be used to determine the actual spin rate. The entire unit may be mounted on a rotatable platform for limited angular adjustments at its assigned viewing port in the shuttle. Application of this device would be limited to providing spin axis and rate information to be used for generation of commands to the despin package for its initial alignment maneuvers upon reaching the target. Although feasibility is still in question, the mechanical strobe offers excellent image resolution continuously and is being studied further.

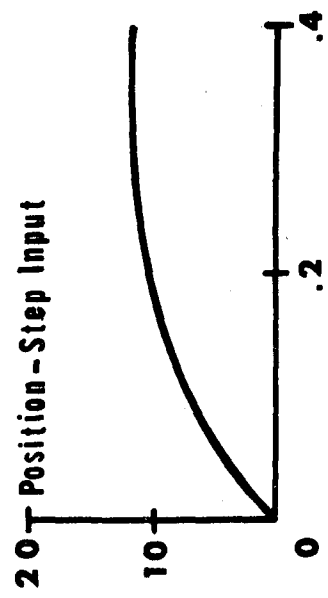
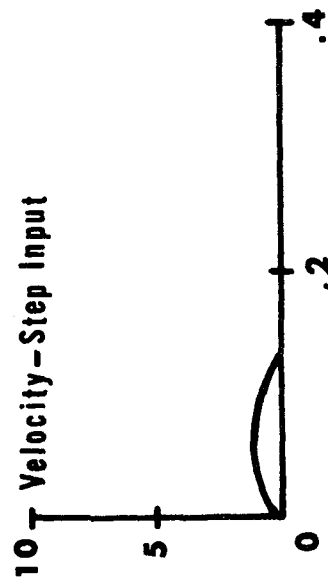
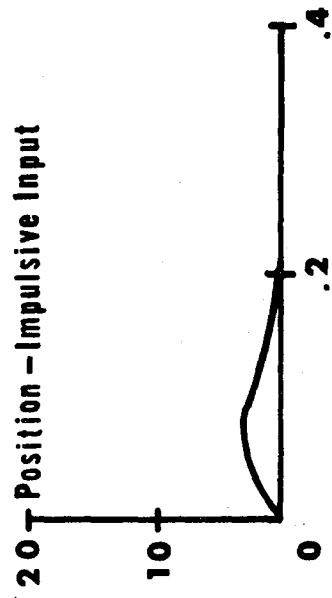
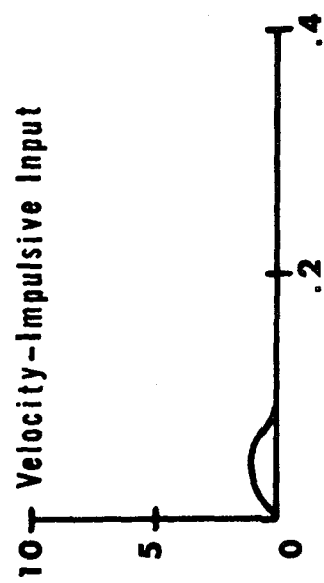


Figure 5. Response of Y-Component Position Control to Impulsive and Step Inputs

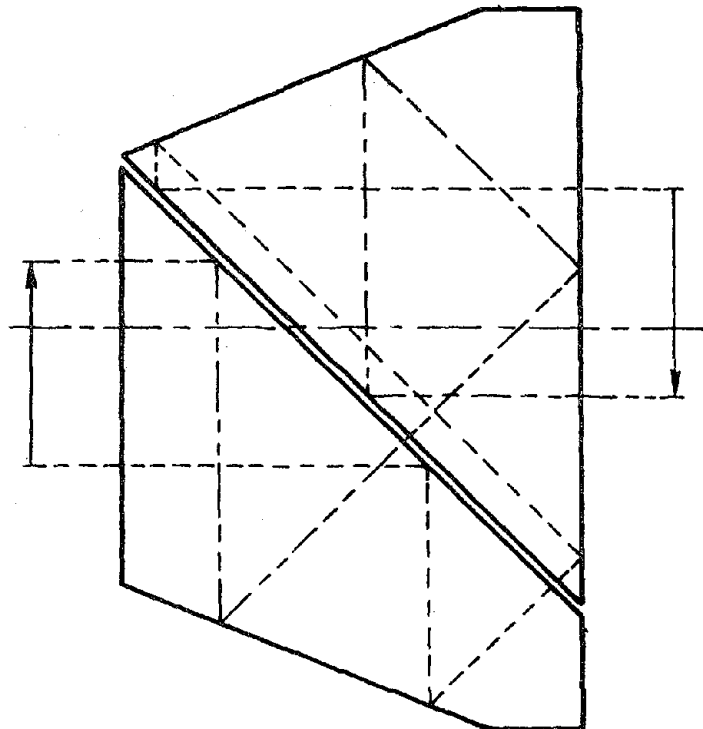
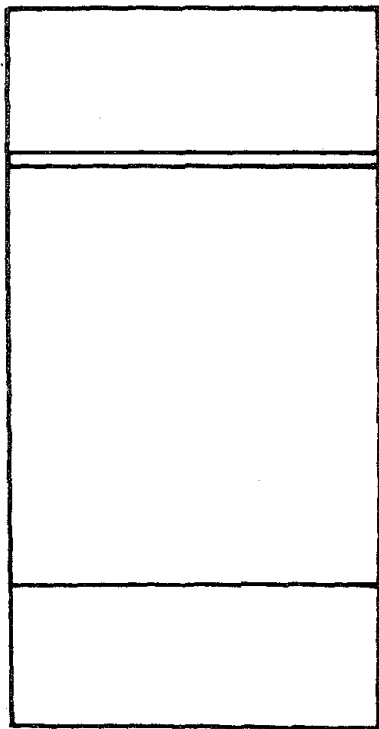
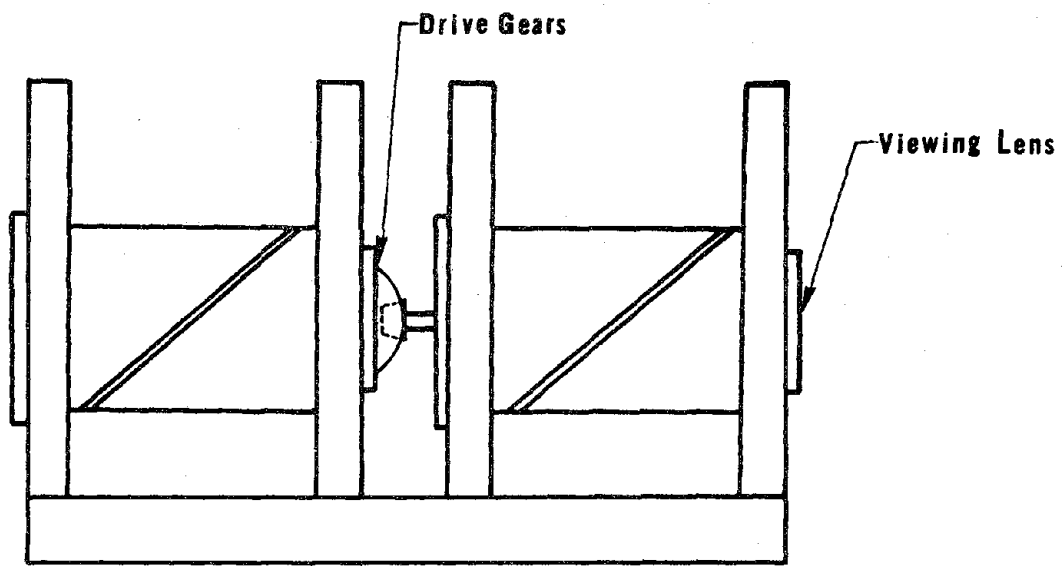


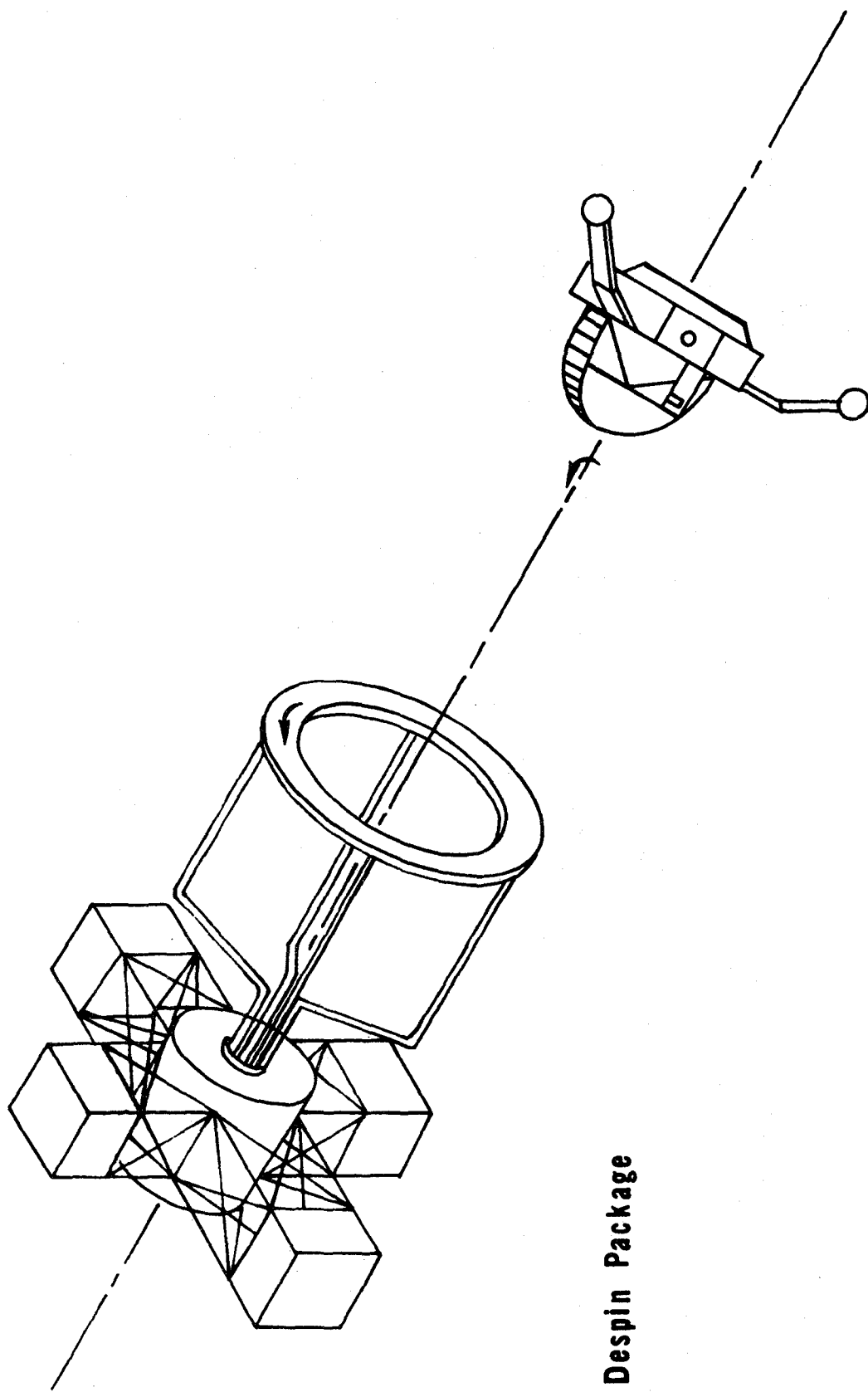
Figure 6. Schematic of Optical Strobe⁸

Final alignment with the object spin axis may be accomplished through the use of two television cameras which provide a bifocal view of the target. The cameras will be focused at a given distance from the target which will permit alignment and stand-off parking simultaneously. When the angle between the spin axis and the center line of the despin package is zero, the axes will be aligned. At this point the television display may be operated in the stop-action mode and cycled at the estimated rate of target spin. Slight desynchronization will cause an apparent rotation of the target about its actual spin axis with frequency equal to the difference between object spin rate and camera display cycle rate. This information is used to make fine adjustments for final alignment by adjusting the display cycle rate to compensate for the frequency difference. The despin sequence may then proceed.

Despin Package

The problem of despinning an uncooperative object has been cited as one of primary interest in this study. The decision to propose a separate device for this operation is the result of safety and performance considerations with respect to the shuttle. With a despin package maneuvering about the object at a "safe" distance away from a manned vehicle, the risk of bodily harm from a mishap is minimized. Crewmen on the shuttle can maneuver a small spacecraft with great ease, especially when aligning the package with the target spin axis.

The despin package is conceived to consist of two major components; tender and despin ring. The tender provides all functions required for orbital transfer and alignment with the target, while the despin ring performs the actual capture of the object. A configuration based on constraints and mission objectives was formulated. The complete spacecraft is illustrated in Figure 7, with tender and despin ring shown in greater detail in Figures 8 and 9, respectively. Overall size of the despin package is limited by the shuttle cargo bay dimensions, proposed to be 15 feet in diameter and 60 feet long⁹. This restricts the ring size and, in turn, limits the size of objects which can be considered for retrieval. However, most objects of interest satisfy this size restriction. The tender is configured to allow maximum applied torque from the reaction control system while permitting large values of inertias about the ring axis. These innovations will minimize propellant requirements and effects of disturbances associated with the



OSO 1

Figure 7. Despin Package Shown During Retrieval of OSO 1

Despin Package

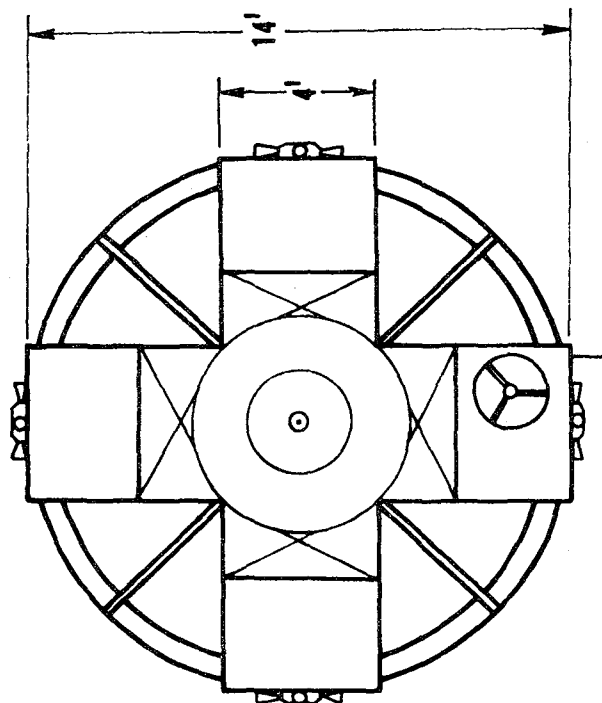
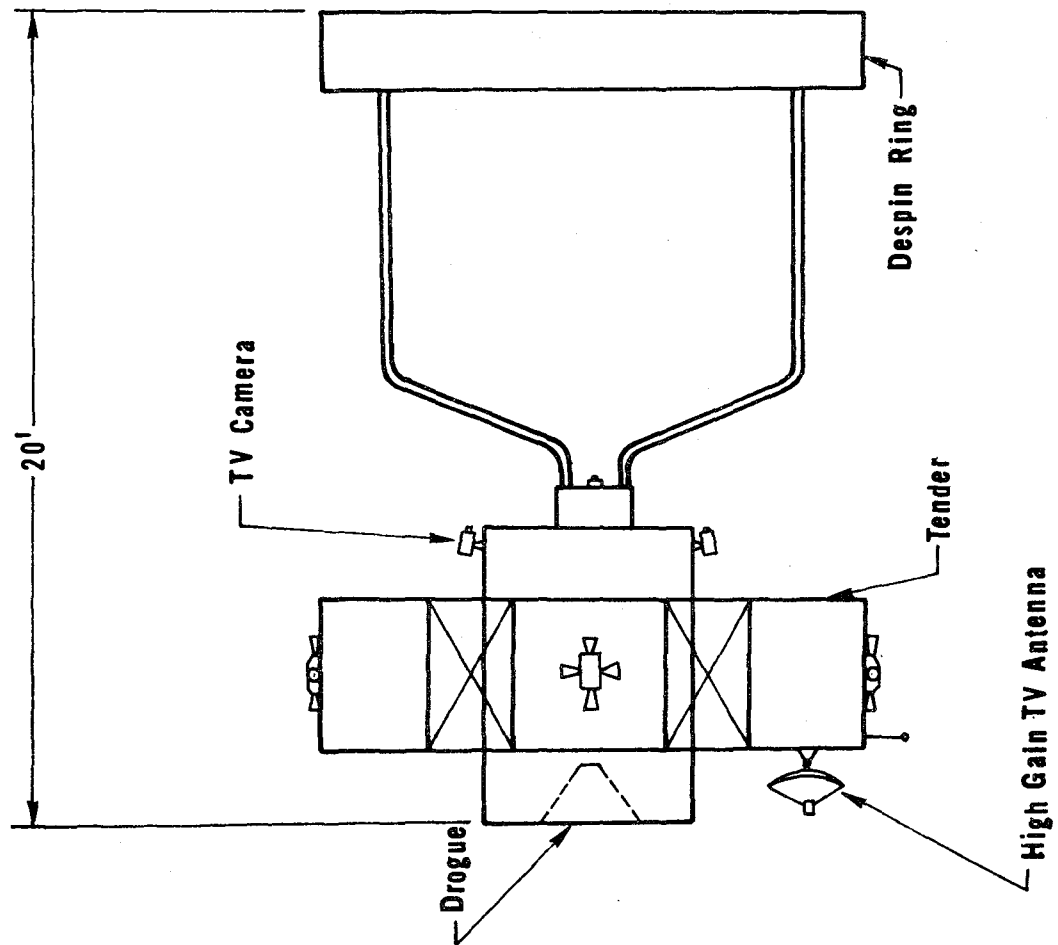


Figure 8. Details of Despin Package Tender Configuration

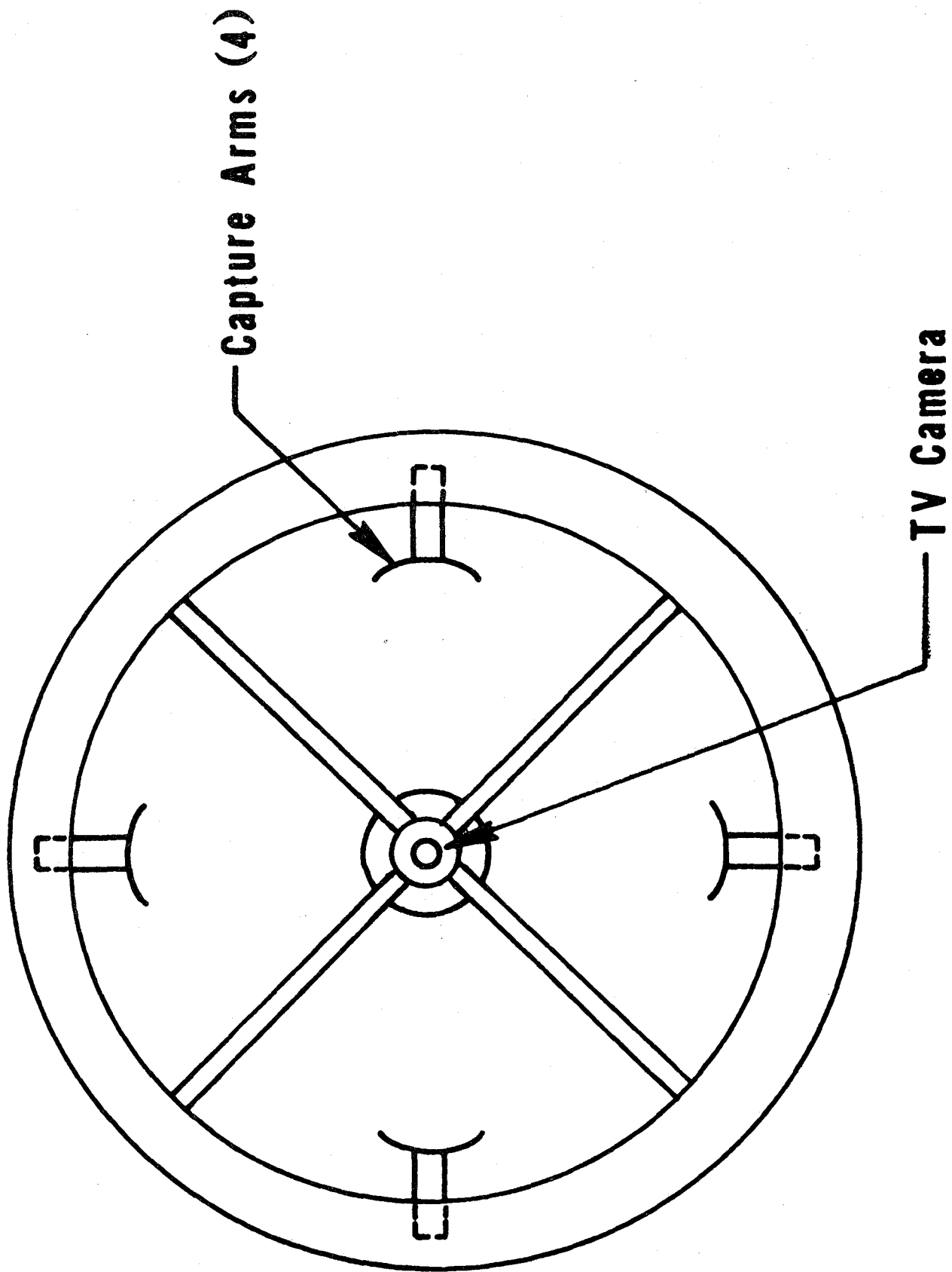


Figure 9. Details of Capture Ring Configuration

despin sequence. Thus, the major dimensions of this main body were selected as 14 X 14 X 8 feet. Compartments in the four arms contain the power system, nitrogen gas reaction control equipment, and command and telemetry system. The central cylinder houses the ring spin motor, twin-gyro controllers for the attitude control system, a reserve nitrogen tank, and docking drogue. The despin ring as conceived here has an inner diameter of 13 feet and an outer diameter of 14 feet. The four docking arms extend inward another foot when in the retracted position. These arms are independently operated to permit capture of arbitrarily shaped objects and can each extend to 6 feet in length. Therefore, objects as small as one foot and as large as 11 feet in diameter can be handled by the same despin ring. Structural support of this ring is provided by four struts as illustrated in Figures 7 and 8.

The subsystems which make up the despin package may be categorized as control, command and telemetry, docking devices, power, and structure. Attitude and orbit control systems, in conjunction with remote commands from the shuttle, provide maintenance of position and orientation during transfer and docking. Twin-gyro controllers were chosen for momentum exchange and nitrogen reaction jets for momentum dumping. Since the tender is inertially oriented in the attitude maintenance mode there is no first order cross-coupling. Cold gas jets have inherently poor performance, but nitrogen gas is relatively safe and easy to handle. Furthermore, the reaction jet tanks are easily refillable before each retrieval sequence. The orbital control system provides thrust impulses for transfer to the target and aligns the package with the target spin axis under commands from the shuttle. Relative position maintenance is performed by remote commands from the crew. Once the package is aligned, capture should be accomplished in a short period of time. Therefore, relative position drift is very slight during this time interval, and an automated position control system is not required.

The command and telemetry system incorporates television cameras and two antennas, an omnidirectional type for the command and telemetry link, and a high gain directional dish for television transmission. The high gain dish imposes some constraint on the shuttle stand-off position in order to satisfy the viewing requirements for this antenna. One camera is mounted along the ring

axis at the center of the support struts, and spins with the ring. This offers a very convenient means of synchronizing ring and target spin rates and provides a check on alignment. Two other cameras mounted diametrically opposed on the central cylinder are used for relative position maintenance through their bifocal properties.

The shuttle/package docking apparatus, shown in Figure 10, consists of a folding arm mechanism with probe, docking latches, and tender drogue. The folding arm extends a docking probe to a position which is easily observable by the pilot. The shuttle then maneuvers to the despin package and upon completion of docking, the package is deactivated and retracted into the cargo bay.

Rescue and Retrieval

The subject of orbital retrieval naturally gives rise to the question of rescue from a space station. Several rescue schemes have been proposed for various emergency situations. The one of interest here utilizes an earth-launched, manned rescue system, i.e., space shuttle specially equipped for such a mission. A typical maneuvering sequence for rescue might be similar to that of a retrieval mission except for despinning and docking. It must be pointed out, however, that an uncontrolled space station which has suffered a significant attitude perturbation will in general be tumbling. There is a distinct and unfortunate difference between tumbling and spinning. The latter is associated with stabilized rotation about a single axis whose direction is inertially fixed and aligned with the angular momentum vector. Tumbling motion is associated with a major misalignment between angular velocity and angular momentum vectors. This situation is coupled with continuous angular motion of all three principal body axes, i.e., no inertially oriented axis. Of course, a tumbling body would reach a stable spin state after a sufficient amount of energy has been dissipated. However, large bodies such as space stations have relatively low dissipation rates and may require several months to passively stabilize.

Astronauts trapped in a tumbling spacecraft could not easily escape and may not even be able to move about inside due to the changing nature of accelerations. Therefore, rescue from such a situation represents a very different problem and one which is likely to arise, because failure of such a station might very well be the result of an explosion or collision. Either event would probably cause

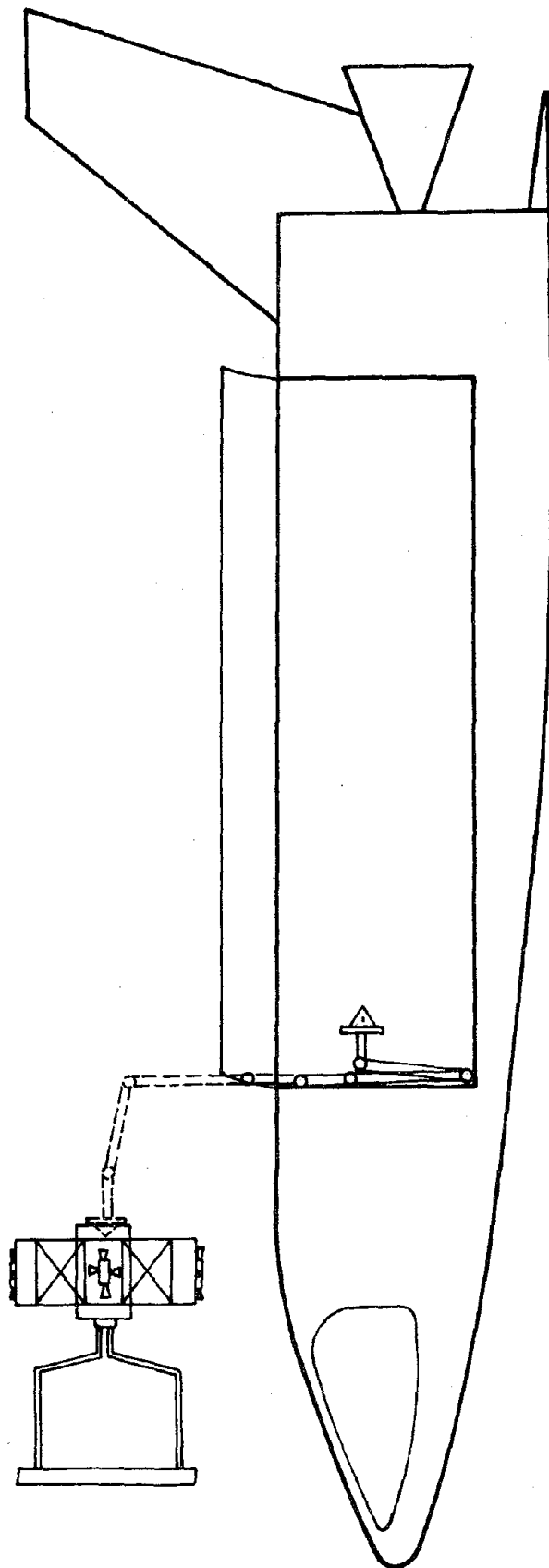


Figure 10. Shuttle/Despin Package Docking Arrangement

tumbling and possible loss of attitude control. It is apparent that spacecraft attitude motion would have to be arrested before rescue operations could be carried out. However, elimination of angular motion of a large tumbling body is a very difficult task, because it must be done from a non-tumbling frame. A "detumbling package" could not move in such a way as to eliminate relative motion, because both the target and detumbling systems cannot simultaneously possess the same center of mass location, principal moments of inertia, and angular momentum components.

The space shuttle offers a fast, economical rescue capability. However, a great deal of innovation is still needed to develop methods for elimination of angular motion of a large body. This appears to be a very difficult task, but one which must be done to fulfill a complete space rescue capability.

Conclusions

Several of the unique problems of rendezvous and docking with an uncooperative object have been considered here. Major areas of concern include the determination of spin axis and rate of an arbitrarily shaped body, and the problem of despinning such an object. Many assumptions about the mission and constraints had to be formulated due to the lack of experience with orbital retrieval and space shuttle operations. The large number of uncertainties associated with retrieving an uncooperative body indicates a definite need for control of the situation by a man. The economic aspects of these missions indicate the use of a reusable transportation system. Therefore, a strong case can be made for space shuttle application to retrieval operations.

The principal contributions of this paper are considered to be the formulation of a general operational sequence for retrieval using the space shuttle, development of spin determination methods, and conceptual design of an unmanned spacecraft which can despin an uncooperative body. In addition, the technique of stand-off parking and intermediate transfer between shuttle and target offers safety and increased maneuverability with respect to despinning an object. Partial application of the methods used in retrieval may be made to the problem of rescue from a space station. The major area of difference is related to possible attitude dynamics of a large manned spacecraft.

Future studies should yield some optimization of stand-off parking positions and transfer trajectories. Further development of the despin package design will produce estimates of physical properties and control system responses for the various attitude and orbit maneuvers required of the mission. Investigations of spin determination methods will eventually lead to a "quick" technique for calculating spin rate and orientation.

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SPACE SHUTTLE

CREW/COMPUTER COMMUNICATIONS

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INTRODUCTION

The control of future spacecraft has reached the threshold of autonomous operations. The development of large manned spacecraft for extended earth orbital flights and interplanetary exploration demands that the capability for more control and mission decisions be on-board. The cost of providing ground control for continuous mission monitoring and evaluation for all future manned space flights will become prohibitive. It will be impractical to dedicate the computer and manpower for the extensive amount of time required by planned future manned flights. With space travel becoming more routine, the feasibility of controlling each vehicle from the ground becomes impractical. The physical size and payload capability of future spacecraft will increase the number of vital functions to be monitored and controlled.

Immediate action in emergencies will require computer diagnosis to assist the crew in determining the proper response. Each of the various spacecraft will be conducting mission peculiar experiments. These experiments will require on-board data reduction and analysis, and the mission timeline will depend upon the conclusions drawn from the data. Therefore, this information must be immediately available for on-board modifications.

Because of the nature of any manned spacecraft, the reaction and decision time are critically short and necessitate that a computational subsystem be an integral part of the spaceship systems. This computer must not only be programmed to automatically control and monitor the spaceship's functions, but must also possess the attributes of speed, accuracy and ease of communication. The computer must be integrated into the information system such that decision data are effectively displayed in a form which can be analyzed instantaneously. Conversely, crew action in responding to alarm situations must be timely and with minimum translation. Therefore, the information system must accept data in a syntax which conforms to the crew's vocabulary rather than that of the computer. Without these inherent features it would be difficult for the spacecraft commander to exercise ultimate authority and responsibility.

The primary objective of this document is to describe the crew/computer interaction (communications) functions and methods required for future space travel. This report summarizes the current results of the Astronaut/Computer Communications Study now in progress at MSFC. The starting point in this task is to draw upon the experience which has been gained in the space programs by evaluating existing and proposed methods of crew/computer interaction. This will result in the characterization of specific criteria to form a study baseline establishing trends from which the degree of computer automation will be extrapolated. The function of each subsystem of the spacecraft will be analyzed to determine the degree of manned and automatic control and their interrelationships.

The ultimate method suggested for future on-board crew/computer communications is voice communications with self-educating computer systems. The methods described in this document are not that exotic but are considered as intermediate solutions to the on-board crew/computer communications. The term

"intermediate" is intended to connote a necessary evolutionary step in achieving the ultimate solution, not to infer that better solutions exist. The methods described in this paper are technically feasible and considered advanced when compared with conventional systems. They reflect proposed hardware and software technology advances anticipated for the period 1973 to 1980. Although the crew/computer interactive methods described herein do not eliminate the needs for knobs and switches as a part of future spacecraft cockpit configurations, they do provide a technique for considerably reducing the present day requirements. Briefly, the crew/computer communication methods presented utilize remote graphic displays for entering data and a technology oriented vocabulary for describing tasks to the computer.

In deriving these techniques, analyses of on-board crew/computer interactive functions and methods were conducted. The functions identified as a result of these analyses are documented in Section 1 of this report, and the methods are discussed in Section 2.

SECTION 1

FUNCTION CATEGORIES

In determining on-board crew functions for future spacecraft, an assumption was made that future spacecraft would be as autonomous as state-of-the-art technology would permit. Ground support functions performed for Gemini and Apollo missions were considered as on-board function requirements for future spacecraft. To compile a composite list of spacecraft functions an in-depth analysis was conducted into the following areas:

- A. Ground support functions required by existing and past spacecraft and space missions.
- B. On-board functions required by existing and past spacecraft.
- C. Proposed functions for Space Shuttle.

A careful investigation of current methods of documenting or listing on-board functions of both aircraft and spacecraft disclosed that several techniques were used. The more conventional methods were organized by mission timeline, mission phase or vehicle hardware subsystems. These techniques were generally voluminous in nature and redundant in content; therefore, the organization of these functions is considered unsatisfactory.

The purpose of the study is to define a structured vocabulary and establish methods by which space scientists or astronauts can communicate with the on-board computer. In identifying the on-board function by technology or disciplines, a structure is established and a direct function, method and vocabulary relationship defined. It is for this purpose that the technique of grouping related functions into categories was adopted.

The eight function categories listed below have been established as a result of the analyses conducted in this study.

Mission Control -- Functions required to monitor and evaluate actual versus planned mission data, and to adjust mission plan or correct vehicle performance as required to achieve desired mission goals.

Data Management -- Functions required to acquire, process, store, maintain and retrieve data as required to support the vehicle and related mission functions.

Communications -- Functions required to select the desired communications media (i.e., radio, television, radar, etc.) and related frequency/channel, antenna, and route of communications.

Flight Control -- Functions required to maintain vehicle attitude and trajectory as required by the flight plan.

Guidance and Navigation -- Functions required to acquire and reduce G&N data so that the vehicle's current versus planned position and trajectory can be determined and the degree of deviation and compensating control functions can be computed.

Experiments -- Functions required to perform, monitor, and control experiments being performed from space vehicle.

Maneuver Management -- Functions required to initiate, execute, and evaluate success of a vehicle maneuver.

Operational Status -- Functions required to monitor and maintain vehicle and crew operational status.

The results of this task support the philosophy that each function category will have its own interactive hardware and language requirements. This is not unreasonable to expect when considering that individual ground disciplines have unique computer/communication requirements and that future space languages will, by necessity, have to be easy to learn and easy to use. Future space missions will find the on-board computer user performing his job functions utilizing language and tools normally associated with his job function and/or discipline. It is also not unreasonable to conceive that all categories requirements can be met with one general purpose graphic display terminal.

Representative function categories determined during evaluation of vehicle subsystems will be described in detail. The intent is to define the functions comprising three function categories of the eight previously defined and to emphasize the requirement(s) for these functions. The format for this discussion will present a pictorial overview of the function category being described with accompanying prose citing examples for clarity. Many of the functions described herein are proposed or anticipated to be operational on manned spacecraft such as the Space Shuttle during time frame 1973 to 1980. For this reason all functions are discussed collectively as if they were operational today.

MISSION CONTROL (Figure 1)

Mission control encompasses all functions and subfunctions that must be performed to assure crew safety and mission success. Basic functions associated with this category are: (1) mission planning, (2) mission performance monitoring, and (3) commanding. Currently, the performance of these functions is a ground support responsibility, but to achieve the degree of vehicle autonomy being proposed for Space Shuttle and to accomplish future manned space missions (Space Base), mission control functions will be required to be performed on-board. This is substantiated by the economics and logistics involved in maintaining a dedicated ground support mission control center.

Mission Planning

Mission planning functions are primarily concerned with the generation and maintenance of the mission timeline, a chronological list of mission events to be performed. The mission timeline also contains the following data related to event performance requirements:

- A. Event support requirements (i.e., subsystems, resources, etc.).
- B. The estimated status of the vehicle and subsystem before and after an event is performed.
- C. Resources and expendables required by the event.
- D. Crew participation requirements.
- E. Ephemeris data associated with the vehicle prior to event execution.
- F. Other necessary data required for judgment decision involving event execution.

The mission timeline is also used as a "yardstick" for measuring mission performance (i.e., actual requirements versus planned).

Timeline Event Analysis -- Before scheduling a timeline event the event requirements must be identified to establish the capability of the vehicle to perform the event. Once this is established, an analysis is conducted of other events already scheduled to identify conflicts which could effect event scheduling and performance (i.e., computing for resources, counteracting events, etc.).

Timeline Event Scheduling -- Once the vehicle is found capable of performing the event, and the timeline can accommodate the event, the event is scheduled. Event scheduling is a tedious task for any event

change. A critical analysis must be made of the timeline to determine exact times available for event execution and should the event being scheduled require a specific time, scheduling conflicts (i.e., resource and subsystem availability) must be resolved via predefined shifting or rescheduling algorithms.

Mission Performance Monitoring

The vehicle "commander" must continuously monitor mission performance, vehicle subsystem status and resource utilization rates. In this manner he is able to make decisions concerning the mission. For past manned space programs (Gemini and Apollo) this activity was performed on the ground with the assistance of a large mission control staff. For future manned space programs this function will be performed on-board with the assistance of the on-board computer and computer software.

Mission Performance -- The performance of the mission is determined by comparing actual data generated by the mission in progress with planned data generated prior to the mission and predicting mission success based on timeline event requirements and new data rates. These functions are performed automatically by the on-board computer by comparing the mission timeline with data obtained directly from vehicle subsystems. In this manner vehicle, crew and schedule performance are determined statistically and displayed for information and action by the flight commander.

Vehicle Subsystem Status -- Monitoring vehicle subsystem status is another function automatically performed by the computer for the "flight commander".

Resource Utilization Rates -- The flight commander will monitor the utilization rates of vehicle hardware and consumables for statistics generated by the computer. The raw data used in computing these statistics is obtained directly from hardware sensors. Interpretation of the computed statistics provides visibility of resource utilization performance.

Mission Commanding

Commanding functions are those decisions made by the "flight commander" in determining the future of the mission being performed. The commander makes the final decision whether or not to continue or alter the planned mission and implements his decision by issuing commands to effected areas. Commands can be verbal orders to crew members, but in many instances commands will be computer oriented functions which are initiated by the commander from the control and display panel on the mission control console.

Continue Planned Mission -- Decisions made to continue the planned mission will be of the more routine type commanding functions that allocate resources, assign tasks and enable computer programs required to maintain the planned mission.

Alter Planned Mission -- If the "flight commander" decides a mission change is required, he must determine: (1) if a modification to the planned mission is adequate; (2) if an alternate mission is possible; or (3) if an abort situation exists? The ultimate decision will be made by the commander considering the mission change requirements and the capability of the vehicle and crew to perform.

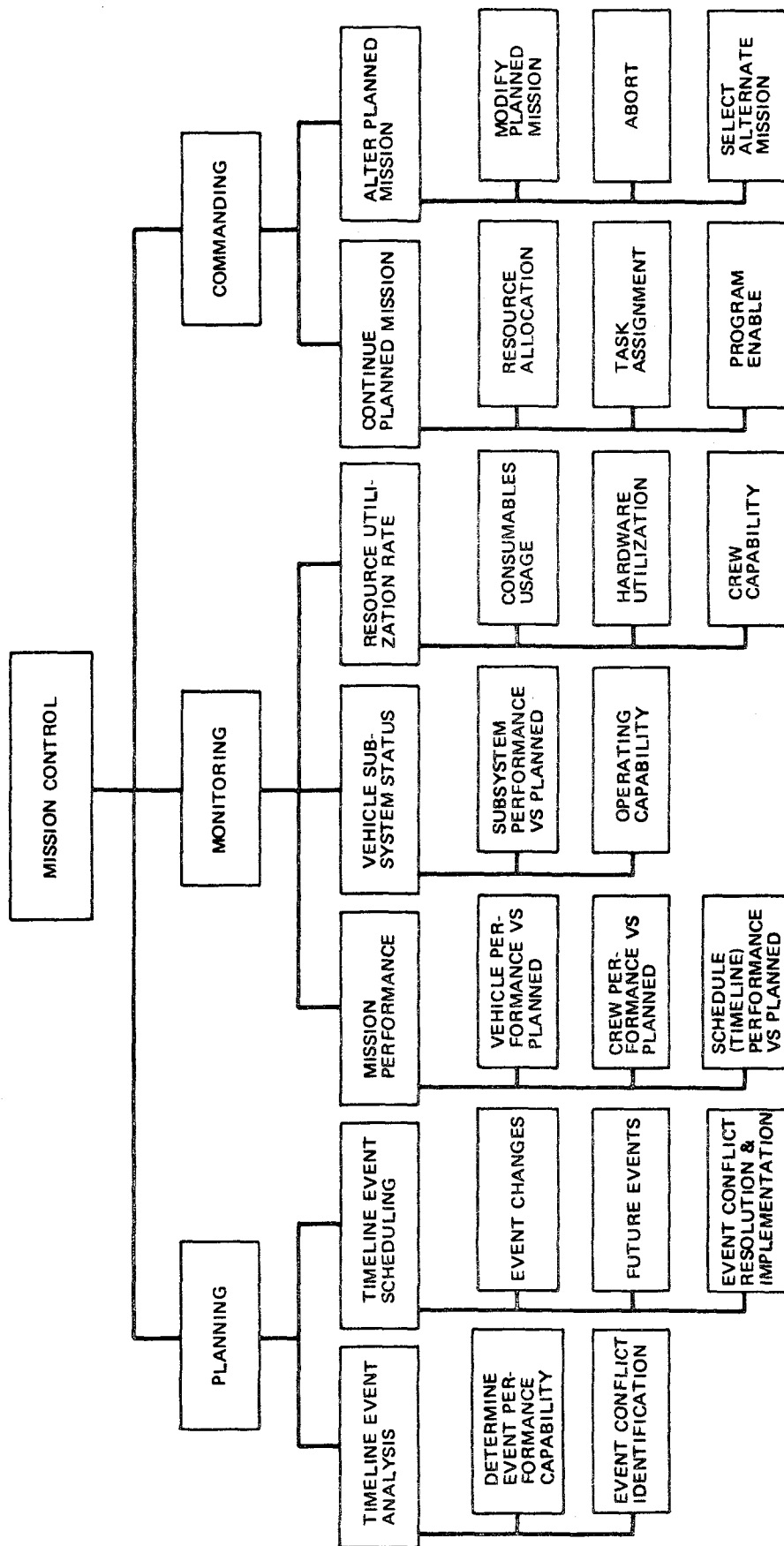


Figure 1. Mission Control Function Breakdown

MANEUVER MANAGEMENT (Figure 2)

Maneuver management is a unique category of functions established to coordinate the various interfacing functions required to identify, define, and execute a vehicle maneuver. In many instances a maneuver requirement will be identified by mission control, in others by flight control. G&N determines the control requirements of the maneuver and flight control performs the maneuver. The responsibility of maneuver management functions is to coordinate function interfaces preparing for the maneuver, executing the maneuver, and evaluating success of the maneuver. The functions described here are distinguished from those discussed under flight control in the flight control is concerned with maintaining a predefined flight path. Maneuver management on the other hand is concerned with rendezvous, docking, station keeping, and other maneuvers which cease to be trajectory oriented.

Preparation

Vehicle maneuvers are scheduled on the mission timeline at sufficient time intervals to allow for the extensive preparation requirements. A checklist of functions must be performed and systems must be initialized in anticipation of the maneuver requirements.

Checklist -- Checklist functions are performed to verify condition requirements of the maneuver being planned. The checklist is an accepted technique for reminding crewmen of the tasks which must be performed in verifying the vehicle's operational status and readiness to perform the maneuver. Checklist functions for manned space vehicles are expanded to include an analysis of the events required to perform the maneuver. This analysis establishes the timing and interactive function requirements for performing the maneuver. The purpose of checklist functions is to minimize, if not eliminate, operating problems once maneuver execution is started.

System Initialization -- Prior to performing a maneuver, vehicle on-board systems must be initialized. This requires that the initial conditions for respective subsystems be set to accommodate maneuver requirements. Some of the subsystems will have components which must be enabled before the components respond. (An example of a component enable requirement would be hardware settings required for abort situations. This enabling technique requires double consideration be given the task being performed.) Software as well as hardware conditions must be initialized. G&N ephemeris parameters must be updated to reflect current status of the vehicle so that any accumulated G&N data errors are corrected prior to the maneuver.

Execution

Maneuver execution functions actually schedule the maneuver, initiate the sequence of events which perform the maneuver, and monitor the maneuver's progress to completion.

Schedule Maneuver -- Maneuver scheduling functions allocate the actual time and time duration for the maneuver, ensuring subsystem and resource availability requirements.

Initiate Sequence of Events -- Initiating the sequence of events is described as that function(s) which is required to issue the control command(s) that will execute the events which perform the maneuver.

Monitor Maneuver Progress -- Future manned maneuver progress functions will be restricted, almost entirely, to computer interpreted and displayed data. Decisions will be based on performance evaluation and data being displayed by the on-board computer system.

Evaluation

Maneuver management requires both pre- and post-evaluation of maneuvers.

Checklist Interpretation -- Pre-evaluation of the maneuver is limited to the interpretation of data obtained as a result of performing checklist functions.

Position Change Review -- Post-evaluation of a maneuver entails a review of the maneuver objectives (i.e., position change) and an interpretation of the success of the maneuver (i.e., were objectives achieved).

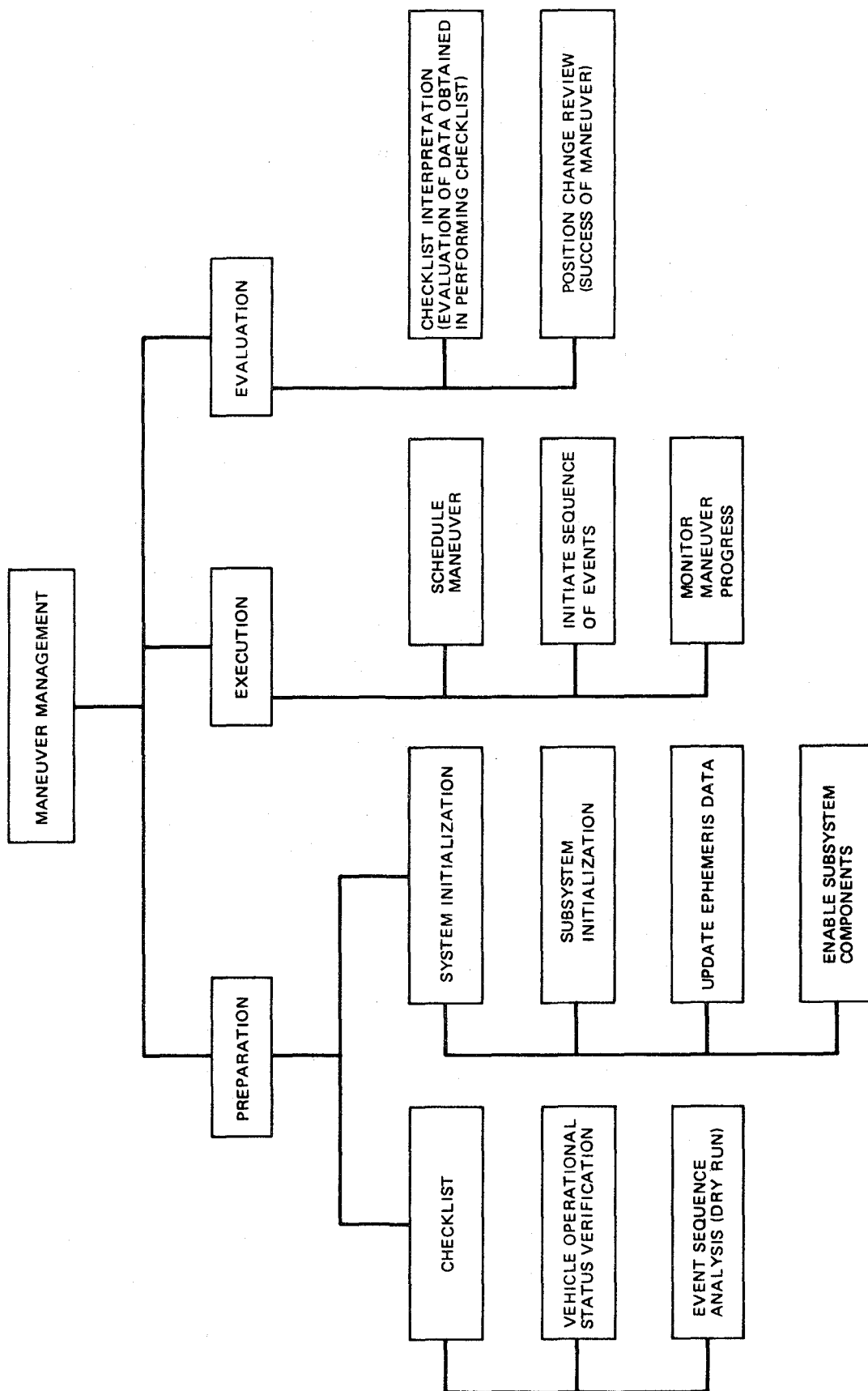


Figure 2. Maneuver Management Function Breakdown

OPERATIONAL STATUS (Figure 3)

Operational status is the term applied to the interactive functions which are performed on-board the Space Shuttle to maintain the vehicle's and crew's operating capability. The requirement for this type of function can be attributed to the proposed mission and vehicle autonomy. To achieve these objectives the capability must reside on-board the Space Shuttle to detect, diagnose and correct sub-performing systems. This requirement is satisfied by the capability provided by the operational status functions.

Crew

Maintaining the operational capability of the flight crew is the concern of the life support and environmental control functions performed to sustain life in a space environment. Crew safety is the major factor in manned space flights, and crew operational status functions are designed to detect and identify for corrective action any symptoms which could prove hazardous to human life. These functions also provide a means for making life in space as comfortable as possible considering the imposed limitations.

Life Support -- Life support encompasses those functions which are concerned with the physical needs of the body. Specifically, (1) is the body medically fit to perform (i.e., mental or physical); (2) are adequate resources available to sustain life (i.e., food, water, oxygen, etc.); and (3) is the waste management system sufficient and operational?

Environmental Control -- Environmental control functions maintain cabin environment as well as space suit environment. These functions maintain a "shirt-sleeve" environment in the space vehicle by controlling the temperature, pressure, and atmosphere within the cabin. Future spacecraft are being proposed to support an artificial gravity system. This function when defined will be considered an environmental control function.

Vehicle

Vehicle operational maintenance functions deal with the more popular subjects of on-board checkout and electrical requirements. These interactive functions permit rapid preflight preparation of the space vehicle and in-flight error detection and correction. Primary requirements for vehicle operational status functions are in response to vehicle autonomy objectives and proposed long duration mission.

On-board Checkout -- On-board checkout is an obvious function which permits on-board hardware subsystem analysis and correction of hardware to the line replaceable unit (IRU). A crewman with the assistance of the on-board computer can detect hardware faults, avoid faults by detecting marginal functioning parts, isolate failures which are not immediately apparent, correct the fault, and verify the success of the corrective action taken.

Electrical -- Electrical functions are separated from those of on-board checkout because of the dependence of on-board checkout functions on the computer which requires electrical power. Rationale is based on the need for trouble shooting power failures in the absence of electrical power. For this reason electrical power is separately considered and assigned functions for determining and supporting total power requirements, allocating the source of power, overall distribution and load leveling of power, and of course, its own optional maintenance system.

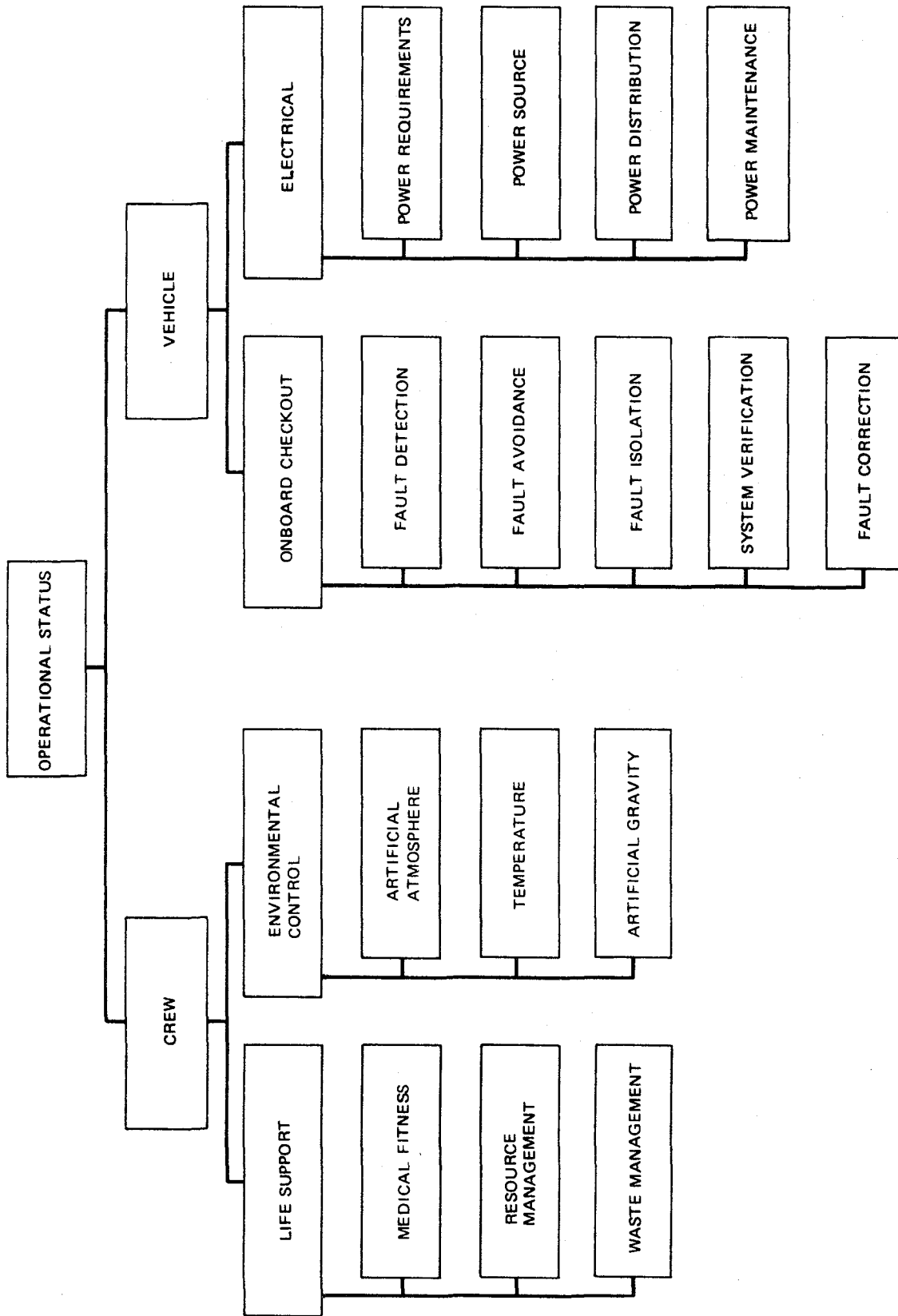


Figure 3. Operational Status Function Breakdown

SECTION 2

CREW COMPUTER COMMUNICATION TECHNIQUES

Early in the study it became evident that no one crew/computer communication method could be devised to satisfy the requirements of all functions in all function categories. The design criteria established for the methods for performing on-board spaceborne crew functions included:

- A. Flexible in Design -- Methods must be "open-ended" for future enhancements and readily susceptible to change for ease in modification.
- B. "Straight-Forward" in Use -- Methods must be easy to learn and easy to apply so as to minimize the training process requirements.
- C. Consistent in Approach -- Methods must be similar in performance requirements for different functions in different function categories, and methods for performing identical functions for different space vehicles must be similar even though the function requirement may vary greatly.

The communication's language developed to support the interactive methods is a technology oriented structured vocabulary (i.e., each on-board discipline will have an indigenous vocabulary for communicating respective function requirements to the computer). Individual discipline languages will be accessible through the use of function and CRT line select keys that provide a conversational means for selecting the desired language level. The conversational approach to obtaining a language allows time for preprocessing software and hardware initialization. Many objections appear when manned space flights are discussed along with conversational crew/computer communications. One must remember that each discipline is being handled separately, and preplanning should solve any critical timing problems.

The vocabulary structure developed will permit on-board computer users to select the language working level conducive to solving the particular problem of interest. The language has a function, command and procedural level of problem solving capability. The "function" level will perform gross task (e.g., display current G&N measurement data); the "command" level performs a more controlled task (e.g., display the vehicle's current attitude using the inertial reference system); and the procedural level will permit finer control over the task being performed. The flexibility generated using this technique centers around the users ability to obtain the exact data he desires and to chain vocabulary segments to perform even more sophisticated tasks.

A crew/computer communication's language is required to overcome the crew/computer interface barrier. Attributes of the language must satisfy the interactive requirements of the graphic-display terminal and computer without placing undue hardships on the crew. The approach adopted by this study as the solution to the above problem was to formulate a function oriented structured vocabulary. The objective being to provide each on-board discipline a unique command vocabulary for performing related interactive functions and eliminate the need for all crewmen to learn a general purpose language and adapt it to their respective job duties.

The structured vocabulary has four distinct levels which parallel the breakdown of function categories presented in Section 1. Figure 4 shows the relationship of the levels and a description follows:

- A. Category -- Refers to eight function categories described in Section 1, e.g., Mission Control.
- B. Function -- The first level breakout of a function category, e.g., Mission Control Planning.
- C. Subfunction -- The next level breakout of a function, e.g., Mission Control Planning - Timeline Event Analysis.
- D. Vocabulary -- The detailed working level is subdivided into two operating modes, procedural and command.

The purpose of the structured vocabulary is to expedite the location and access of the desired function language. This is accomplished through keyword association of job functions to technology language. Another advantage of a structured vocabulary is that it's easy to program, and adapts to an interactive environment.

The vocabulary level operating modes, "procedural" and "command", permit the user the option of constructing a complete function for automatic execution or performing each task serially. The latter affords the user greater control over the function being performed by providing intermediate task results for analysis before proceeding to the next task.

To facilitate further discussion of Space Shuttle crew/computer communication methods, a minimum hardware configuration of a remote graphic-display terminal is presented (Figure 5). This particular configuration was selected after analyzing the common communication requirements of the functions listed in Section 1.

This graphic-display terminal configuration provides an instrument for discussion and developing a communication's vocabulary. A discussion of the crew/computer hardware/vocabulary interactions are explained in the following paragraphs.

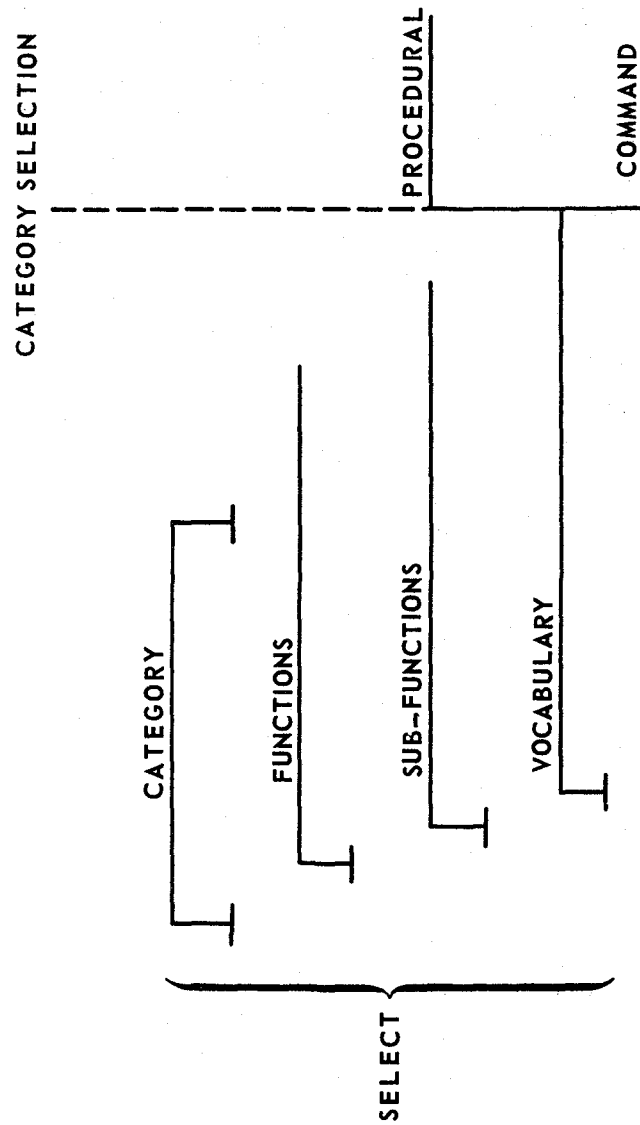


FIGURE 4 VOCABULARY STRUCTURE BREAKDOWN

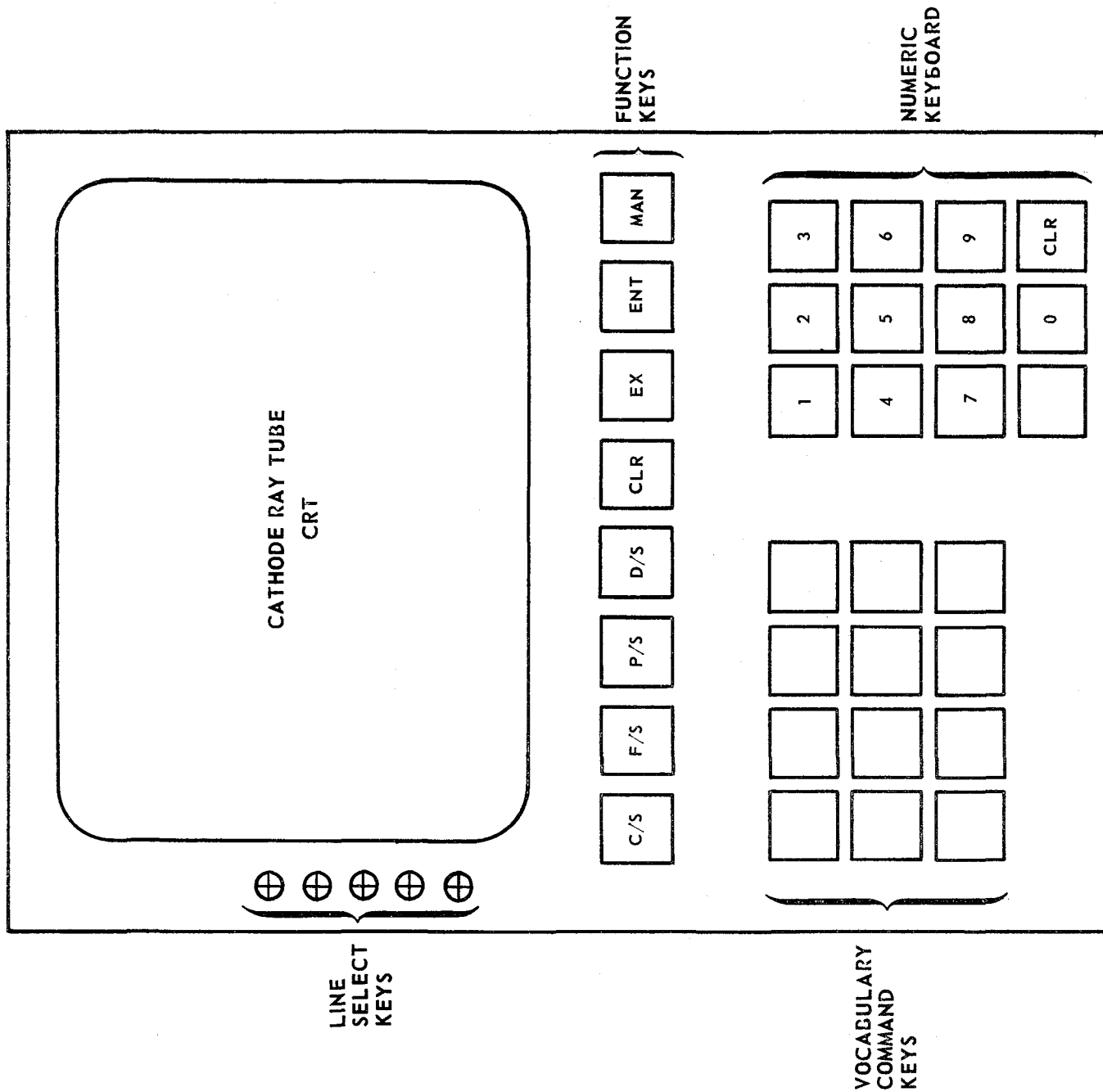


FIGURE 5 REMOTE GRAPHIC DISPLAY TERMINAL

Procedure Mode

Reentry procedure for landing at Eglin; alternate Marshall;
timeline update is auto; retro burn setup is 06:07:45:23.
(execute)

Command Mode

<u>Keys</u>	<u>CRT Option</u>
Category Select	Maneuver Management Reentry
Function Select	Preparation
Command Key	
Landsite	
Primary	Eglin
Alternate	Marshall
Timeline	(Retro burn setup)
Execute	Sequence Checklist
Execute Function	Reentry Sequence

The crewman inputs reentry data then computes a dryrun of the reentry event. After dryrun sequence is set for execution and starts monitoring procedure.

SUMMATION

The primary objective of this research effort was to develop advanced crew/computer communication methods applicable to manned spacecraft such as the Space Shuttle. It is felt that this objective has been achieved and is represented by the defined structured vocabulary. Development of a "computerized" structured vocabulary consisting of on-board technology oriented languages has become feasible with the advent of language compilers. McDonnell Douglas is currently producing such a compiler which provides a means for defining syntax in terms of a computer's machine language. The compiler generates a software system which is capable of recognizing and analyzing statements written in the defined syntax. The syntax can now be used to communicate function requirements to the computer. The McDonnell Douglas language compiler, referred to as a Syntax Directed Compiler (SDC), is being developed in Huntington Beach, California, and implemented at Marshall Space Flight Center, Huntsville, Alabama. The significance of this technique is that individual languages can be expanded and/or changed without affecting other languages or the operating system. These techniques as presented in this document have been implemented at MSFC on an IBM 7094 and at MDAC-St. Louis in a Space Shuttle simulator. Through these efforts this technology has proven effective and usable.

As a result of the above efforts, MSFC is planning to extend and/or expand the vocabulary to meet specific needs of the Space Shuttle missions.

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HOW TO ASSURE SAFE MISSION TERMINATIONS

Henry Wolf
M. Vele

Grumman Aerospace Corporation

I. INTRODUCTION

While commercial aircraft only provide egress on the ground, Mercury, Gemini, and Apollo spacecrafts had to have launch escape systems to remove astronauts from potentially catastrophic situations. The Earth Orbital Shuttle is similar to commercial aircraft in that it will carry passengers and cargo and fly in the atmosphere; yet, its other operations are more akin to those of a spacecraft. This aircraft/spacecraft aspect of the shuttle raises the question of how to design for escape from the shuttle should emergency conditions arise. A study of Grumman's G3 design for a two-stage reusable booster and orbiter was conducted to gain insight into this question.

This paper will show that:

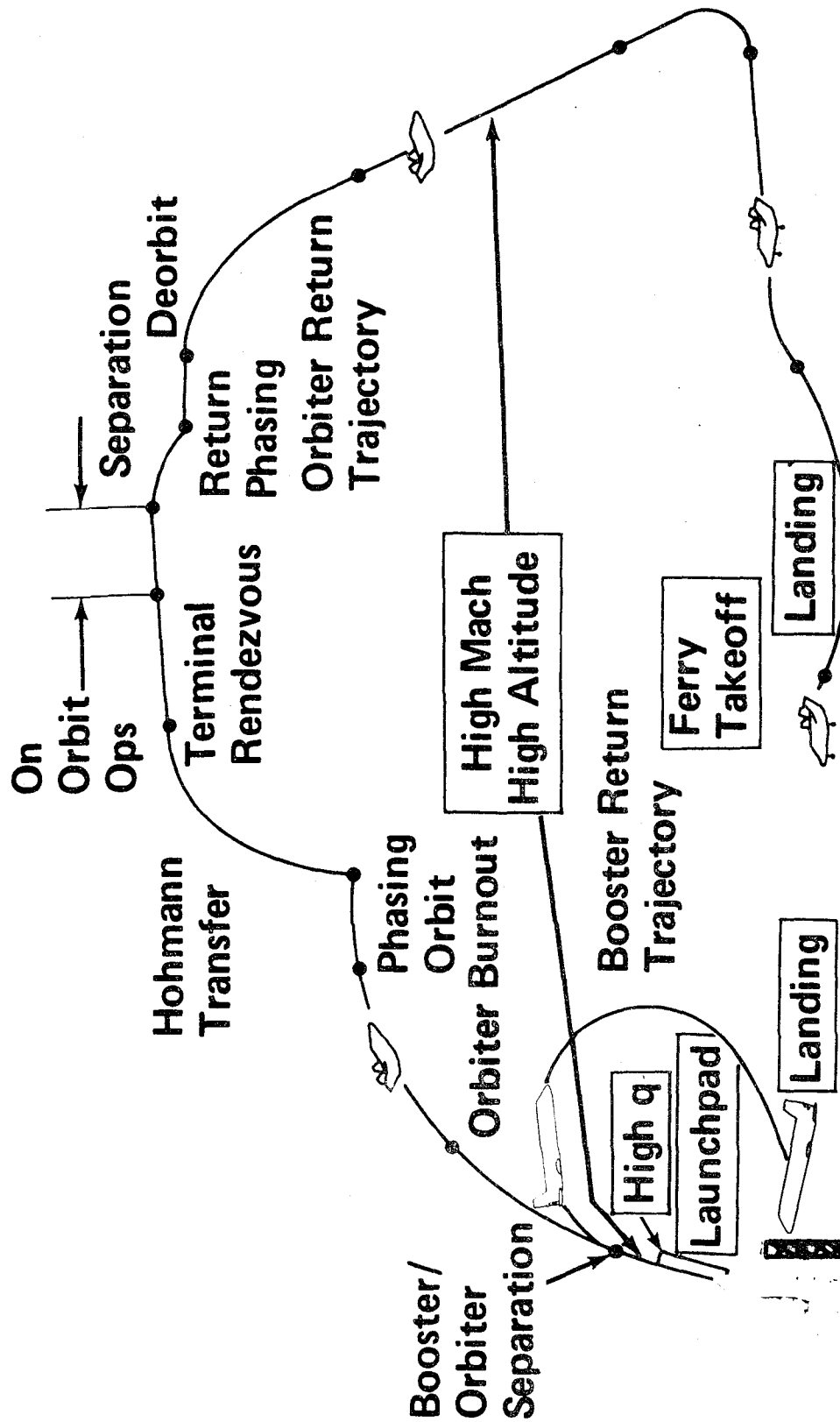
- o Situations do exist requiring escape provisions.
- o The launch pad, landing, and ferry flight takeoff are escape critical regions.
- o Sufficient warning of an imminent explosion is crucial to safe escapes.
- o The three manned compartments present no unique escape problems.
- o The orbiter-flyaway-booster-escape-capsule concept seems to be a reasonable approach for development flights and nominal operations.
- o Ejection seats may be required for orbiter development flights.

II. CRITICAL MISSION PHASES

Though the entire mission was studied, the phases that are most critical from a 'time for crew escape' viewpoint are (See Reference 2):

- Launch Pad. The period after propellant loading when the crew and passengers board, terminal countdown is initiated and completed, lift off occurs, and initial 15 seconds of flight to 1200 feet is completed.
- High g. The region 30-100 seconds after lift off where the combination of air density and vehicle velocity produces a peak of 400 to 500 pounds per square foot dynamic pressure on the external structure.
- High Mach - High Altitude. The region where nominal separation occurs between the booster and orbiter and the place where an abort reentry may have to be initiated. This point will be amplified in the body of the paper.
- Landing. Whereas other prior spacecraft have returned to earth via parachute, the shuttle will land like an airplane. Therefore the period from reaching high key, an altitude/velocity position where approach to the landing site is initiated, to rollout on the runway is critical.
- Ferry Flight Takeoff. For a variety of reasons ranging from prime landing site bad weather to an intact abort, the shuttle may land at a place other than the prime landing field. It is then necessary to return the craft to its launch site. This requires a ferry flight from the alternate to the prime site. The initial roll for take off to the achievement of cruise altitude is also considered a critical phase.

CRITICAL MISSION PHASES



TIME AVAILABLE FOR CREW ESCAPE
MAKES THESE PHASES CRITICAL

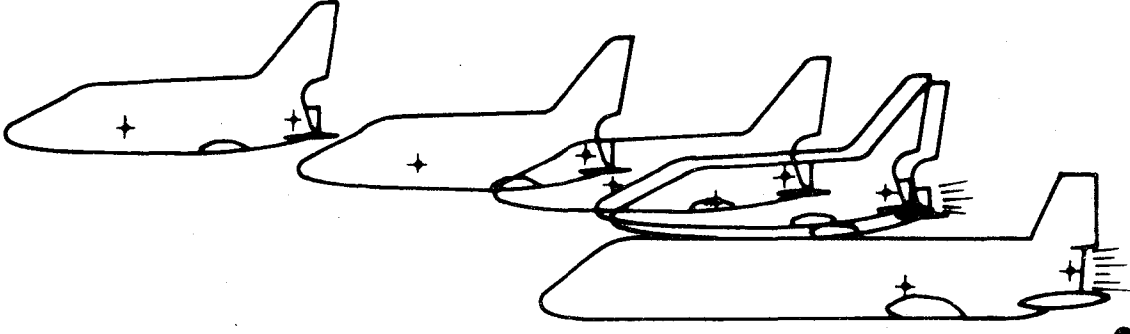
Booster/Orbiter Separation

The separation maneuver is mission-critical in nominal and abort cases. Launch pad separation is an especially hazardous operation. The separation technique used is as follows. As the booster engines are throttled back toward zero for the nominal case, or to some level above 50% of full thrust for aborts, the orbiter engines are ignited. They achieve full thrust a few seconds later.

At the point where the thrust-to-weight ratios for each vehicle equal, the force required to separate the vehicles is a minimum. The separation mechanism pushes the vehicles apart at the right instant with the orbiter thrust increasing to 100% and the booster thrust dropping to some required level.

BOOSTER/ORBITER ABORT SEPARATION

- **Set Booster/Orbiter Thrust to Weight Ratios Equal**
- **Provide Time for Separation Mechanism to Work**
- **Let Orbiter Engines Develop Full Thrust**
- **Minimum Operation Time ~ 6 Seconds**



SEPARATION IS A PRECISE MANEUVER

III. HAZARD IDENTIFICATION

A requirement for escape provisions exists when vehicle-crew capabilities cannot compensate adequately and in time to save the vehicle from damage and the crew from injury if they remained with the vehicle.

A matrix of critical mission phases from an escape viewpoint versus potential catastrophic hazards is shown. The selection rationale was based on whether the estimated probability of occurrence of the hazard was greater than one in a million per mission (Ref. 1). It should be noted here that we are describing 'what if' situations. By knowing the possible hazards in advance of the final design, meaningful effort can be made to avoid, or at least minimize, the chance of the hazard occurring. In some cases a calculated risk may be necessary.

HAZARD MATRIX

Hazards	Mission Phase				
	Launch Pad	High q	High Mach High Alt	Landing	Ferry Flt T/O
Unprogrammed Motion	X		X		X
Loss of Attitude Control	X	X	X	X	X
Loss of Elec Power	X	X	X	X	X
Unhabitable Cabin Environment	X			X	X
Hard Landing				X	
Implosion			X		
Inflight Collision			X	X	X
Explosion	X	X	X	X	X
Fire	X			X	X

MISSION PHASE DETERMINES HAZARD CRITICALITY

Hazards and Their Potential Sources

It is estimated that each of the hazards can be triggered by one of several events. The hazards and typical potential sources are listed.

HAZARDS AND THEIR POTENTIAL SOURCES

Hazard	Typical Potential Source
<ul style="list-style-type: none"> ● Unplanned Motions <ul style="list-style-type: none"> - MPS Hardover - Loss of Thrust (MPS) - Loss of Thrust (A/B) - Launchpad Tipover ● Loss of Attitude Control <ul style="list-style-type: none"> - Loss of TVC - Loss of ACPS - Loss of Aerosurface Cont 	<p>Control Electronics Failure</p> <p>Plumbing Failure</p> <p>Plumbing Failure</p> <p>Sequential Release of Tiedowns</p> <p>Throttle Servo Failure</p> <p>ACPS Turbomachinery Failure</p> <p>Loss of Hydraulic Fluid</p>

IDENTIFY YOUR HAZARD SOURCES

HAZARDS AND THEIR POTENTIAL SOURCES (CONT)

Hazard	Typical Potential Source
<ul style="list-style-type: none"> ● Loss of Electrical Power ● Unhabitable Cabin Envmt ● Hard Landing ● Implosion ● In-flight Collision ● Explosion ● Fire 	<p>OMS Plumbing failure</p> <p>Fire</p> <p>Landing Gear Won't or Can't Deploy</p> <p>Main Tank(s) Evacuated While on Orbit</p> <p>Air Traffic Interference</p> <p>Propellant Leak</p> <p>Propellant Leak</p>

IDENTIFY YOUR HAZARD SOURCES

Estimates of Available Correction or Escape Time

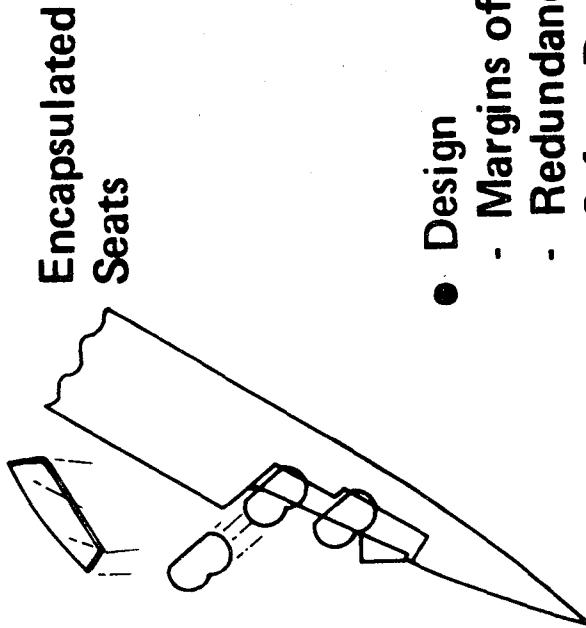
Continuing the 'what if' analysis, it is now necessary to determine how much time is available to the crew and passengers to either take action to save themselves and the vehicle or to initiate escape procedures. In this chart the hazards are compared against the critical mission phases and an estimate of response time is presented for each case. The chart shows that, in general, the slower the speed and the lower the altitude, the shorter the response time available to take corrective action. Hence 'Launch Pad', 'Landing', and 'Ferry Takeoff' are the most crucial phases in which to provide escape capability.

ESTIMATES OF AVAILABLE CORRECTION OR ESCAPE TIME

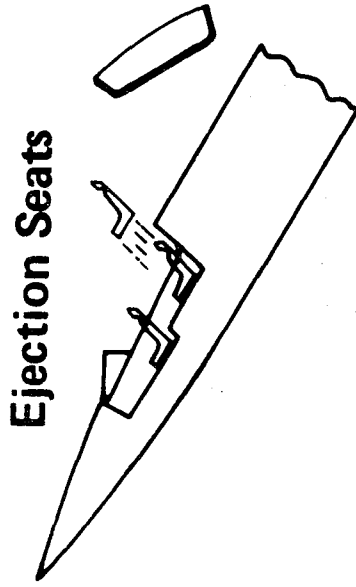
Hazard	Response Time			
	Launch Pad	High q	High Mach High Alt	Ferry Takeoff
Unplanned Motion	1-2 Sec		Sec to Min	5-10 Sec
Loss of Attitude Control	1-2 Sec	Sec	Sec to Min	Sec
Loss of Elec Power	1-2 Sec	Min	Min	Sec
Unhabitable Cabin Environment	2-3 Min			Min
Hard Landing				Sec
Implosion			Min	
Inflight Collision	Sec		Sec	3-5 Sec
Explosion	1-2 Sec	Sec	Sec	2-3 Sec
Fire	Min			Min

AVAILABLE TIME DETERMINES THE RESPONSE

HAZARD COMPENSATION



Encapsulated
Seats



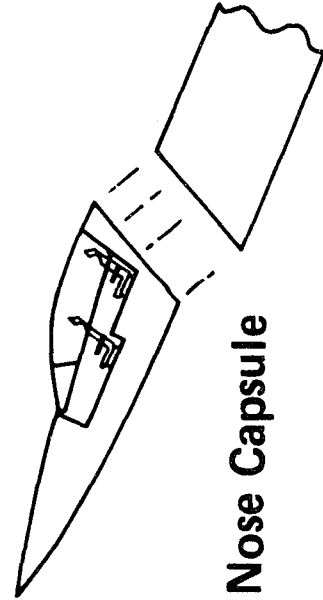
Ejection Seats

● Design

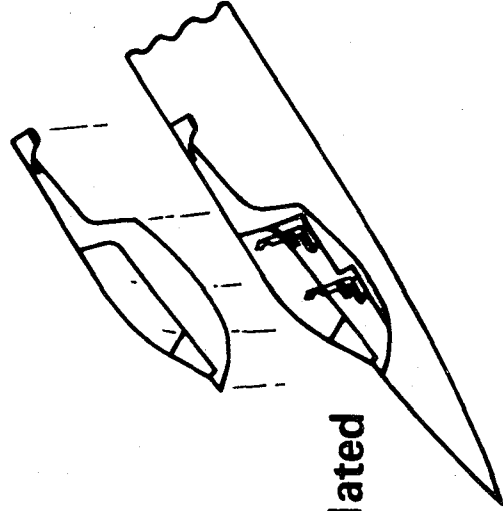
- Margins of Safety
- Redundancy
- Safety Devices
- Warning Devices
- Intact Abort
- Escape

● Operations

- Special Procedures
- Intact Abort
- Rescue
- Escape



Nose Capsule



Encapsulated
Pod

ESCAPE PROVISIONS GUARANTEE SURVIVAL

Inherent Abort Capability

The first abort region is a pad abort during the period cabin closeout to ignition. The primary technique for non-critical aborts in this mode is evacuation via the egress ramps and the high speed elevators of the gantry.

Minimum safe separation altitude is the next region covering the time from ignition to the end of the first 13 seconds of flight. The character of the region is low altitude and velocity. Separation of the orbiter from the booster during this period is highly hazardous to both vehicles.

The next region is one of high dynamic pressure, occurring from 30 to 100 seconds after liftoff. The ability to separate while in this region is currently under study.

If we assume that separation is feasible, the abort technique consists of performing a high altitude (greater than 100,000 feet) coordinated turn and firing all main engines until all propellant is depleted (main and OMS propellant).

The abort region between $t = 156$ seconds and $t = 188$ seconds is characterized by low dynamic pressure ($q \sim 40$ psf) and strong shock waves. An abort separation during this region requires orbiter downrange landing site capability. Like all previous abort modes, this mode also requires propellant depletion in order to reenter safely. The technique for this abort mode is to increase the ΔV in order to bring the vehicle weight down to within the reentry boundaries.

The abort region between separation and orbiter insertion is characterized by vacuum conditions. During this time frame, reentry due to a contingency situation becomes extremely complex because of lack of appropriate landing sites. Like all previous abort regions, reentry requires the depletion of all insertion and on-orbit propellants except for those which must be carried for APS, ECS, and EPS operation. The vehicles have the inherent capability of dumping propellants through the main engines (liquid hydrogen at the rate of 10 lb/sec and liquid oxygen at the rate of 30 lb/sec at 20 psi tank pressure). However, this rate is not sufficient to maintain vehicle trim. Since entry is not possible during this period, the technique for the "one engine out" case is to thrust with the remaining engine to attain orbital velocity. Entry would then occur on the first pass (once around).

Hazard Compensation

At this point the situation may seem "fraught with danger". As stated before, though, if the condition is known, meaningful effort can be made to do something about it.

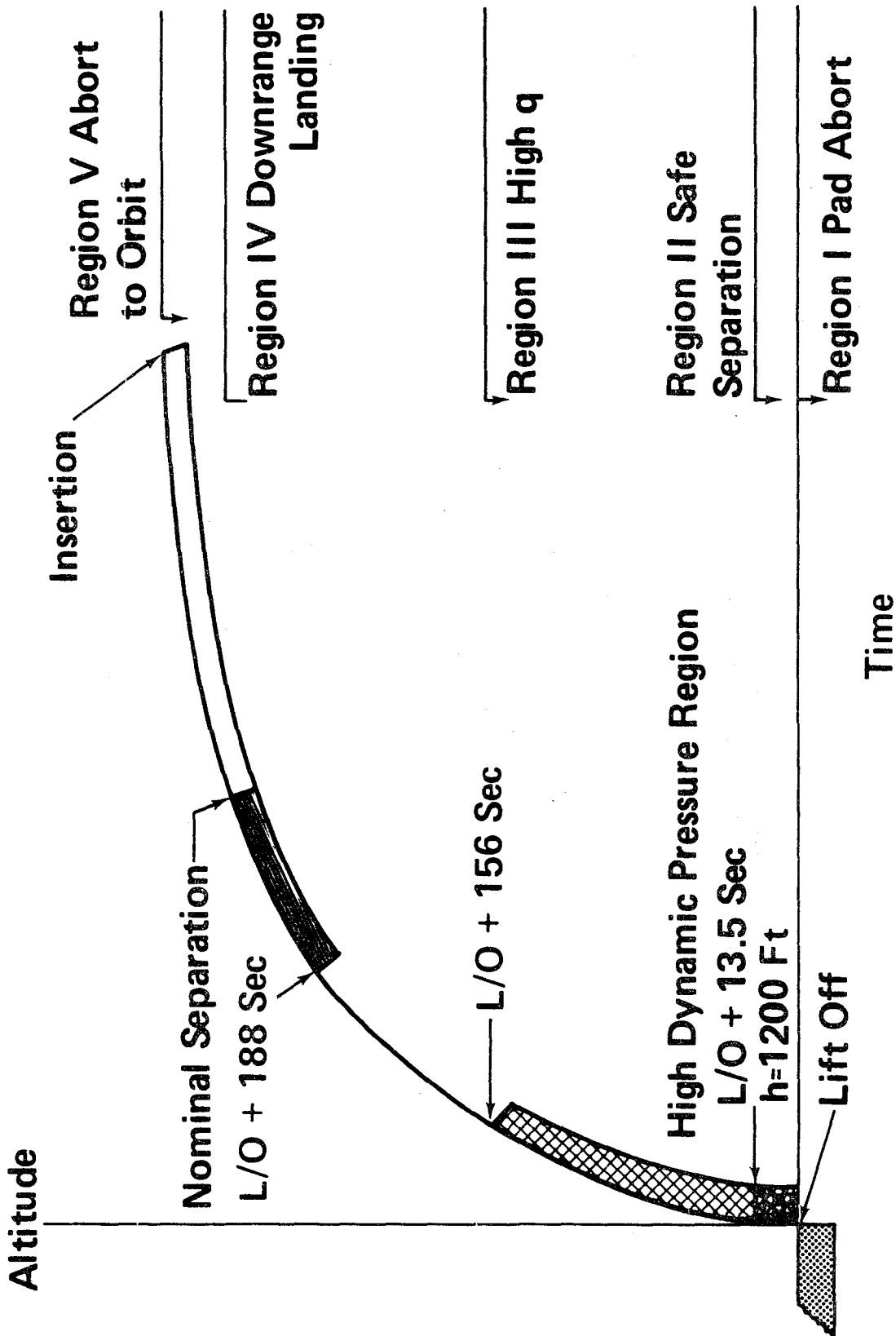
Hazard compensation can be categorized into "design features" and "operational activities". Design features imply inherent qualities of the vehicle included by the vehicle designers. Operational activities are those which the users, the crew and passengers, introduce by utilizing the vehicle capabilities. A few groundrules for the design and operation of the vehicles are outlined here:

- Man's role on board both vehicles is that of an independent controller, supported and augmented by automatic, programmed systems.
- Man will change programs, make decisions, and select alternate uses of the equipment provided.
- Malfunction information will be automatically provided only to the onboard crew and, where appropriate, to the passengers.
- Vehicles will be designed to operate autonomously.
- Abort and escape provisions will include consideration of the affect of the unmanned vehicle's impact on the general population in the area.
- The order of precedence between vehicle commanders will be predetermined prior to flight. Both stages and all three manned compartments will be ready, systems armed, and action (to abort or escape) completed when initiated from either crew cabin.

Our concern is with the relationship between intact abort and escape requirements and provisions. We have hypothesized that current inherent design features and operational characteristics may be inadequate in providing the desired level of safety.

IV. HAZARD COMPENSATION

INHERENT ABORT CAPABILITY



INTACT ABORT IS NEEDED FOR ALL REGIONS

V. ESCAPE MODES AND TECHNIQUES

If a need for an escape system is assumed, then it is necessary to select the conditions which the design must satisfy. The event selected to establish requirements is explosion on the launch pad at liftoff. This event was selected because:

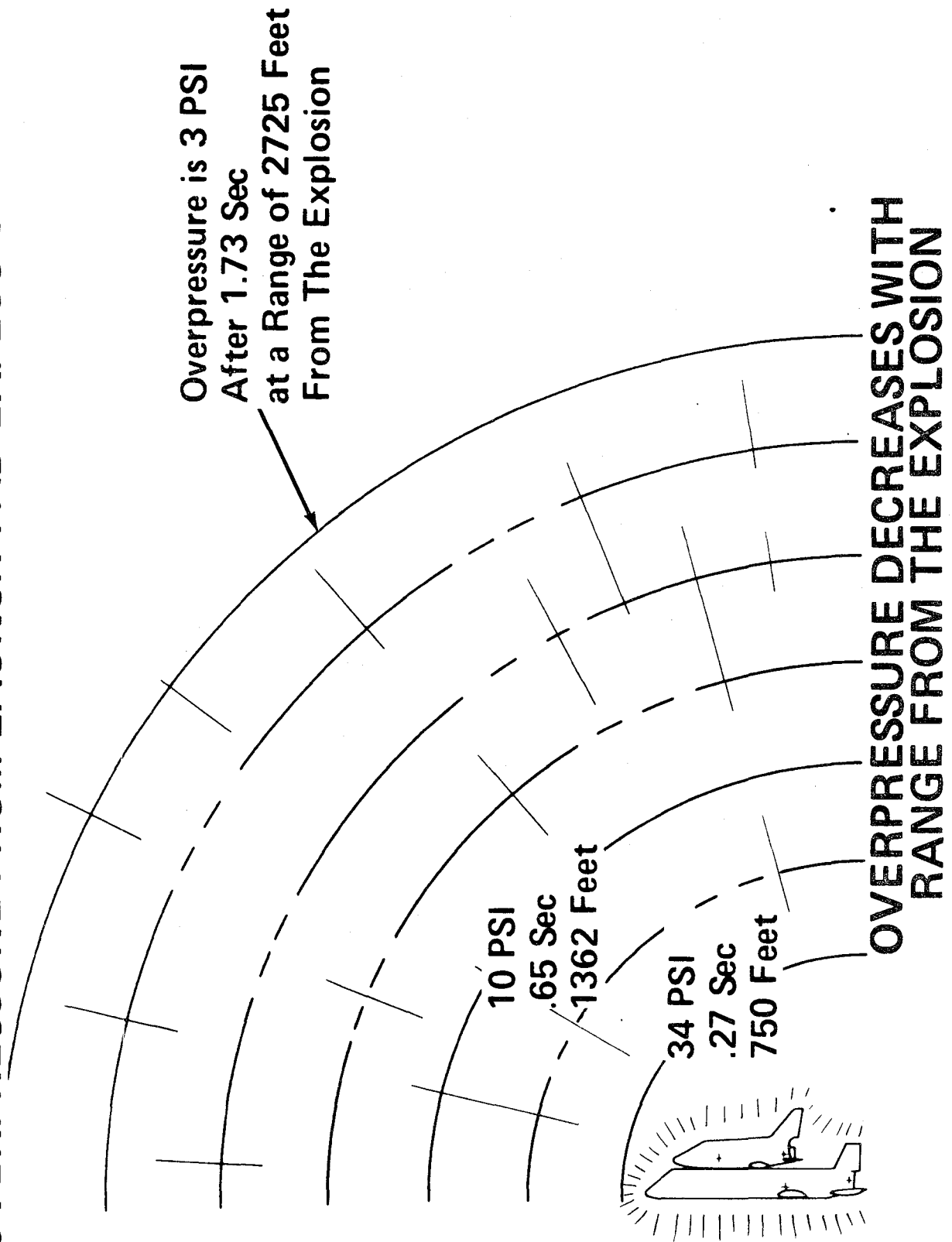
- Fuel quantities are at a maximum
- Maneuver capability is severely limited
- Higher ambient pressure causes larger dynamic pressures
- Low altitude and velocity limits time available for action

In addition, the analysis presented below has shown that if the escape system design satisfies the above event in terms of human safety, it will also satisfy the other critical escape conditions.

Overpressure from Launch Pad Explosion

The primary requirements are to remove crew and passengers safely from a launch pad explosion and to deliver them far away from the effects of the blast in a timely manner. The overpressure conditions are presented as a function of range and height for a ground burst condition (per Reference 4 technique). 3 psi overpressure was selected as a safe threshold because it is equivalent to shuttle operational structural requirements; escape system structure was assumed to be similar to shuttle structure.

OVERPRESSURE FROM LAUNCH PAD EXPLOSION



Human Acceleration Limits

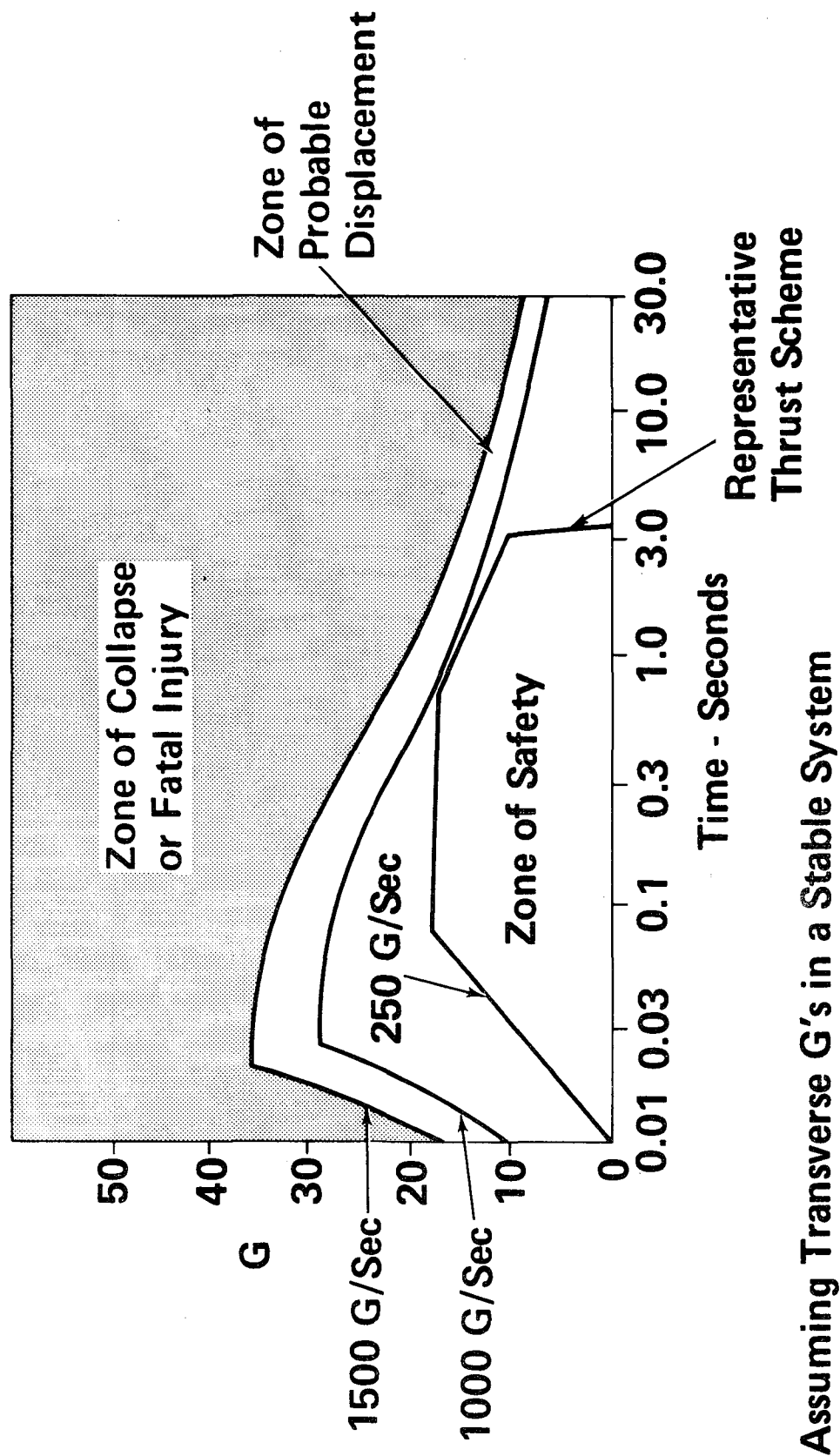
In the situation hypothesized, it will be necessary to gain time to remove the crewmen and passengers from their predicament by using the maximum allowable accelerations that man can tolerate. The zone of safety, the maximum allowable application of acceleration, and a representative thrust scheme is shown.

For example, if we design for attaining a separation distance of 3000 feet in two seconds (Case 1), we subject men to a fatal 46.5 'g'. If we design to MIL-S-18471D, the Ejection Seat specification (Case 2), we impose 18 'g' at an initial rate of 250 'g'/second on the men. 3 'g' is never exceeded for the orbiter flyaway case (Case 3).

Warning time is required if a safe separation distance is to be achieved without crew injury. Warning times for the three cases are:

Case 1.	0 second
Case 2.	1.25 - 2.0 seconds
Case 3.	24.5 seconds

HUMAN ACCELERATION LIMITS



Assuming Transverse G's in a Stable System

ACCELERATION MUST BE APPLIED SELECTIVELY TO MEN

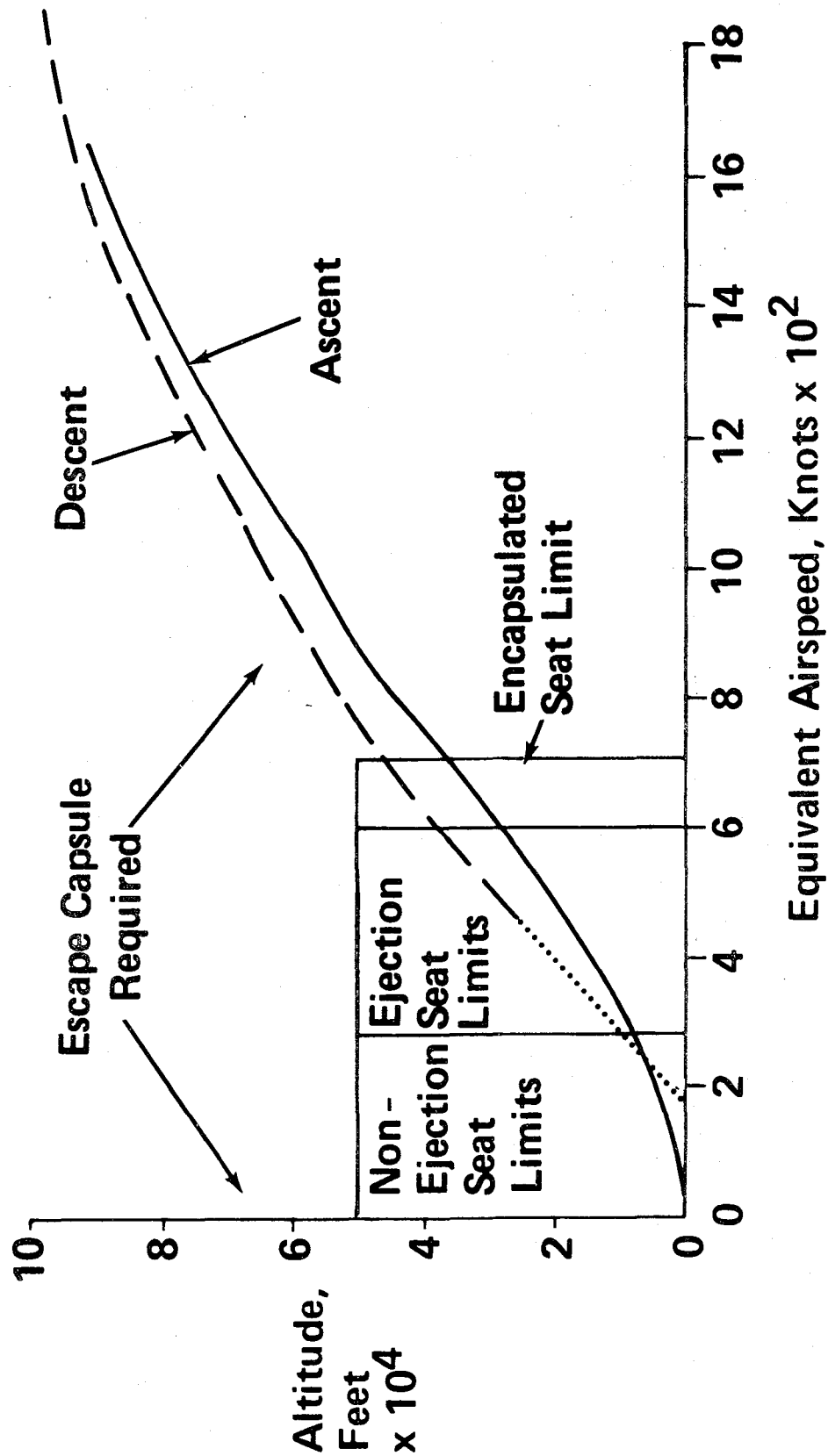
Escape Provision Requirements

The altitude versus airspeed for nominal ascent and descent was plotted on the Air Force Escape Provision Requirements diagram. It is seen that for the speed and altitude range of the shuttle escape cases, an escape capsule or at least an encapsulated seat is required. Abort/escape operations occur at speeds in excess of 600 knots and altitudes up to and beyond 100,000 feet.

Other escape system design requirements can be listed briefly as follows:

- Provide aerodynamic stability in the regions of expected use
- Provide a stabilization and control system
- Provide a minimum separation interference
- Provide protection against high temperature heating environments
- Provide for safe impact on land or water
- Provide a communications system and emergency life support
- Apply acceleration forces during escape in a transverse (back-to-chest) or longitudinal (feet-to-head) direction, whichever is the safer one
- Restrain crewman's arms, legs, and torso in order to preclude injury during the escape
- Provide a personnel locator system for rescue after escape
- Exercise control over the impact area of the unmanned vehicle after escape initiation
- Provide an escape trajectory which is compatible with all possible mission uses

ESCAPE PROVISION REQMTS VS SHUTTLE ASCENT/DESCENT PERFORMANCE



SHUTTLE REQUIRES AN ENCAPSULATED SEAT OR AN ESCAPE CAPSULE

Escape System Envelope

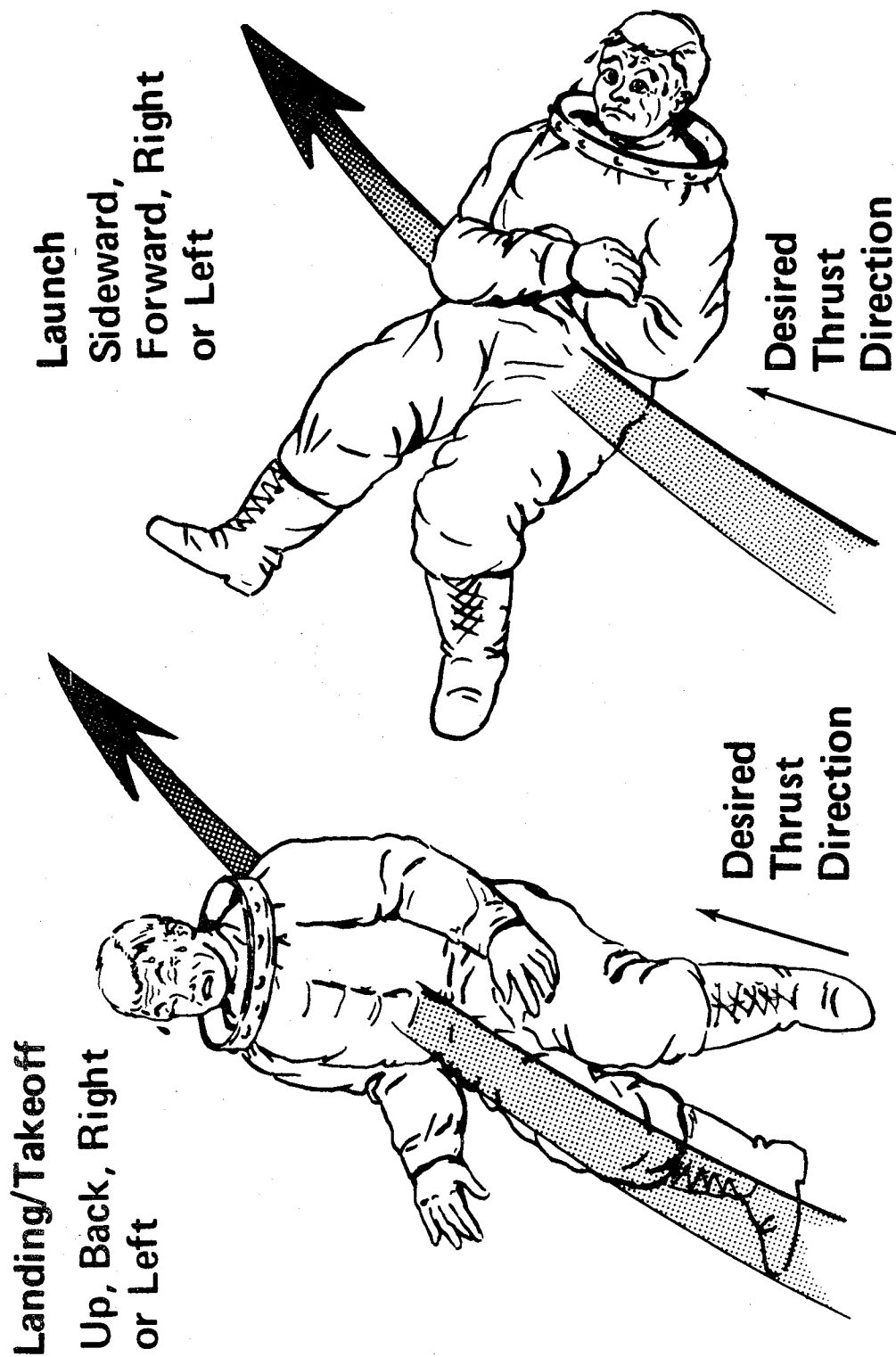
Two views of the thrust geometry for three of the critical escape phases are shown. They are incompatible. For the launch pad case, the trajectory is directed sideward, forward, and right or left of the vehicle. For the landing and takeoff cases, the trajectory is up, back, and right or left. The launch pad trajectory is inappropriate for the landing/take-off case because of the possibility of crew-vehicle collision after ejection.

Several suggestions can be made that eliminate this incompatibility:

- Design two separate thrust systems, one for each escape mode
- Design a two position thrust system
- Offset the gantry to provide a clear escape path around the stack. Design the thrust system with a thrust vector control (TVC) capability
- Design a fall-away gantry and provide TVC in the escape thrust system

Should the escape system requirement be accepted, these alternatives must be further evaluated before arriving at a final design concept.

ESCAPE SYSTEM ENVELOPE



LAUNCH AND LANDING/TAKEOFF ESCAPE ENVELOPES ARE INCOMPATIBLE

VI. DESIGN CHOICES

Our design choices for the shuttle escape provision consist of the following approaches:

- Avoid or control the hazards. Increase redundancy to commercial airline levels (FO/FO/FS) and design for intact abort.
- Conclude that the booster crews are subjected to great danger. Design for booster crew escape via an ejection seat or capsule and assume the orbiter will be able to fly away.
- Conclude that the risk of danger (10^{-6}) is too great (See Reference 3). Design escape provisions for both vehicles, either ejection seats for all, or one capsule each for the booster crew, orbiter crew, and passengers, respectively.

Design Concept Assessment

The results of an evaluation of the various concepts are shown. The evaluation criteria used were:

- Procedural Complexity. Estimates the number and difficulty of steps required to respond to a hazardous condition
- Unreliability. Estimates the probability the system will not work when required
- Weight. Estimates the possible payload loss from incorporating a specific design
- Unuseable region. Estimates the flight and/or mission region for which a concept would not be applicable

The number in the lower left of each matrix box represents its rank for that criterion.

DESIGN CONCEPT ASSESSMENT

Criteria	Increased Redundancy	Orbiter Flyaway Booster Seats	Orbiter Flyaway Booster Capsule
Procedural Complexity	Switch Equipment in or Out 1	Orbiter Separate; Sequential Seat Ejection for Booster 3	Orbiter Separate; Capsule Eject 2
Unreliability	Switching Network Reliability Critical 1	USN '60 - '69 12.5% Malfs Resulting in Fatalities 4	Simple System 2
Weight	Booster & Orbiter One Additional Equipment Set Each ~57,000 lb 5	Two Ejection Seats ~2500 lb 1	Two Man Capsule ~3000 lb 2
Unuseable Regions	Probability of Hazard Decreases. No Capability if Hazard occurs 3	700 Knots 60 000 Feet Alt Max Range 4	Covers Entire Booster Flight Envelope 2



DESIGN CONCEPT ASSESSMENT (CONT)

Criteria	All Ejection Seats	All Capsules
Procedural Complexity	Sequential ejection Passengers Orbiter Crew Booster Crew 5	Sequential Ejection Passengers Orbiter Crew Booster Crew 4
Unreliability	USN '60-'69 12.5% Malfs. Resulting in Fatalities 5	Simple System, But Three Units Must Operate 3
Weight	14 Ejection Seats ~17,500 lb. 3	Booster 2 Man Caps. Orbiter 2 Man Caps. Passengers 10 Man Caps. ~21,000 lbs 4
Unuseable Regions	700 Knots 60 000 feet Alt. Max Range 5	Covers Entire Flight Envelope 1

VII. DEVELOPMENTS CONSIDERATIONS

Prior to subjecting the vehicles to manned orbital flights they will be processed through a series of full scale tests. Horizontal flights and suborbital launches will be used to obtain verification of the aero-thermodynamic characteristics of the vehicles. In the horizontal test phase, ferry and/or flyback airbreathing engines will be used throughout the flight regime for the orbiter (25,000 feet and 300 knots) and the booster (14,000 feet and 300 knots). Aerodynamic characteristics and handling qualities for the powered and unpowered flight configurations will also be determined.

The purpose of the suborbital flights is to verify design characteristics of the thermal protection system. The vehicles will be launched in a mated configuration into a sub-orbital ballistic trajectory.

Development Flights

It is considered prudent to provide an extra measure of safety during development flights. For this reason, two ejection seats should be added to the orbiter. A linear-shaped charge system could be used to cut egress hatches in the cabin should they be needed. This would minimize the vehicle scar, an orbiter design guideline.

DEVELOPMENT FLIGHTS

Criteria	Design Concept: Ejection Seats/Capsule
Procedural Complexity	Sequential Ejection: Orbiter Pilot, Commander Then Booster Capsule
Unreliability	Simple System, Yet Three Units Must Operate
Weight	5500 lb
Unuseable Regions	Covers Entire Booster and Partial Orbiter Flight Envelopes

CONSIDER DEVELOPMENT FLIGHT REQUIREMENTS

VIII. SUMMARY AND CONCLUSIONS

In summary, Launchpad, Landing, and Ferry Flight Takeoffs constitute the most escape critical regions in the shuttle missions. Development flight tests can contribute other hazardous conditions in addition to these.

There are situations that require escape provisions.

The three separately manned compartments present no unique escape problems if orbiter flyaway and booster ejection operations are assumed. Warning at least two seconds for the booster and 24.5 seconds for the orbiter before an imminent explosion is of course the keystone of crew escape safety.

The design choice which seems to provide maximum safety for the crew/passengers and minimum impact on the shuttle design is the orbiter-flyaway-booster-escape-capsule concept.

Development flights may require the addition of orbiter ejection seats for the flight crew.

In conclusion, Grumman's normal design for safety practices will include compensation for those hazards that can be identified during the system evolution. However the risks that may be required during development flights and the critical mission phases dictate consideration of a booster escape system and an orbiter launch pad flyaway capability.

SUMMARY & CONCLUSIONS

- **Summary**
 - **Launchpad, Landing, and Ferry Flight Takeoffs are Escape Critical Regions**
 - **Situations Exist Requiring Escape Provisions**
 - **The Three Manned Compartments Present No Unique Escape Problems**
 - **Sufficient Warning of An Imminent Explosion is Essential to Safe Escapes**
 - **Orbiter Fly Away, Booster Escape Capsule is the Preliminary Design Concept Selected**
 - **Orbiter Ejection Seats May be Required for Development Flights**
- **Conclusions**
 - **Grumman's Design for Safety Compensates for Identified Hazards**
 - **Development Flight and Critical Mission Phase Risks Dictate Consideration of Booster Escape Capsule and Orbiter Launchpad Flyaway Capability or Crew Ejection Seats**

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A PROPOSED INCIPIENT FIRE AND TOXIC GAS CAUTION
AND WARNING SYSTEM FOR SHUTTLE

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A PROPOSED INCIPIENT FIRE AND TOXIC GAS CAUTION AND WARNING SYSTEM FOR SHUTTLE

Introduction

Fire detection in the pre-Shuttle era has been on an after the fact basis. This situation has not only plagued the Aerospace industry, but has been the norm in almost every facet of industrial technology. While great strides have been made in the past fifteen years in the fire prevention area by the development of non-flammable materials, there are still many cases in engineering and design which precludes the use of non-flammable materials. While the fire hazard is markedly reduced it still exists. Therefore, both the designer and engineer must give careful considerations to the what, where, and how materials are used in any system whether for earth or space use. In fire prevention, one must consider how to control the fuels, that is, its non-flammability in the anticipated environment. Electrical shorts and other ignition sources must be minimized. In addition, the amounts and placement of flammable materials must be adjusted so that if a fire does occur, catastrophic events are prevented. As long as the designer and engineer are cognizant of these factors for ground system use, he can generally accept some calculated risks. Or, if he wishes to go one step further he might add a fire warning and control system which will provide an additional time factor in order to react to put out the fire, since pre-combustion and combustion times are generally of longer duration on earth. However, in space, it is another matter to both control and prevent fires since secondary problems of smoke, toxicity, and escape become major factors in personnel logistics. Therefore, along with trying to have the best non-ignitable materials and configuration, your ultimate goal in space is to buy time for the crew to react in case a fire is about to occur. The problem of buying time at present has no easy solution because technology has lagged in this area. I'm sure that my previous statement may be cause for some heated discussion; however, when all of the factors are taken into account, all fire and smoke warning devices have vulnerable spots. Even those devices now available which call themselves fire precursor warning methods are subject to question. All the devices in both categories mentioned are either non-specific, that is, subject to interferences or they are insensitive. Thus the false alarm nature of these techniques markedly decrease their usefulness because in space we cannot afford to cry Wolf.

Discussion

NASA has been looking into the area of fire caution and warning systems quite carefully in the past few years. While we don't claim any panacea in this area, we are looking at some rather interesting techniques which could result in a possible breakthrough in the area of buying time for either the Shuttle or Space Station crews (Figure 1). We have classified fire detectors as primary and secondary types. While several of the systems that are called out have obviously been around for some time, they are worthy of consideration for certain applications. In addition, we believe that in-depth testing is required to uncover their advantages and disadvantages. This re-evaluation is being done to probe through the smoke laid down by our sometimes over zealous salesmen. I do not intend to cover the world of detection but rather address myself to one rather interesting system which we at MSFC have been studying for the past two years. That is the correlation spectrometer/interferometer technology as it applies to fire precursor and toxic gas detection for Shuttle.

Figure 2 shows a typical fire curve. Primarily for some undefined time, depending upon conditions, the ignitor and fuel tend to heat up. During this process, pyrolysis products are formed which vaporize into environment. As the material continues to increase in temperature, prior to its reaching its autoignition temperature, smoke is produced giving a possible visible indication of impending fire. At the material's autoignition point, the vapor being produced will burst into flame accompanied by an increase in heat and pressure. Figure 3 compares the fire risk in space versus earth.

The major problem facing the successful implementation of remote optical detection is the rejection of background spectra. While suitable sensitivity is available for the gases of interest, the large number, and at present totally unknown concentrations of other gases in the Shuttle, drive the instrument design toward the ultimate available specificity. A difficult route to follow since there is insufficient criteria for how good the system needs to be. However, this chasm does not seem to be unbridgeable based upon in-house studies at MSFC and the available results of Contract NAS8-26197 with Arthur D. Little, Incorporated. From these data, it appears that correlation spectrometer/interferometer techniques is one of the most promising of all available systems (Figure 4).

While the ultimate in sophistication would be a scanning correlation interferometer with computer data reduction and readout, this concept cannot be developed within the time frame of the Shuttle. In order to obtain the maximum in specificity and sensitivity, keep the packaging, and power consumption to a minimum with high degree reliability, it was decided that the best approach to home in on, for the immediate future, was

PRIMARY TYPES

CONDENSATION NUCLEI COUNTER

IONIZATION DETECTORS

SMOKE DETECTORS

CORRELATION SPECTROMETER/INTERFEROMETER

UV/IR DETECTORS

CONTINUOUS WIRE THERMISTORS

TEMPERATURE SENSITIVE PAINTS

TRACER ELEMENTS

SECONDARY TYPES

THERMAL CONDUCTIVITY BRIDGE

CATALYTIC WIRE BRIDGE

MASS SPECTROMETER

GAS CHROMATOGRAPHY

R.F. DETECTORS

Figure 1. Types of Fire Detectors

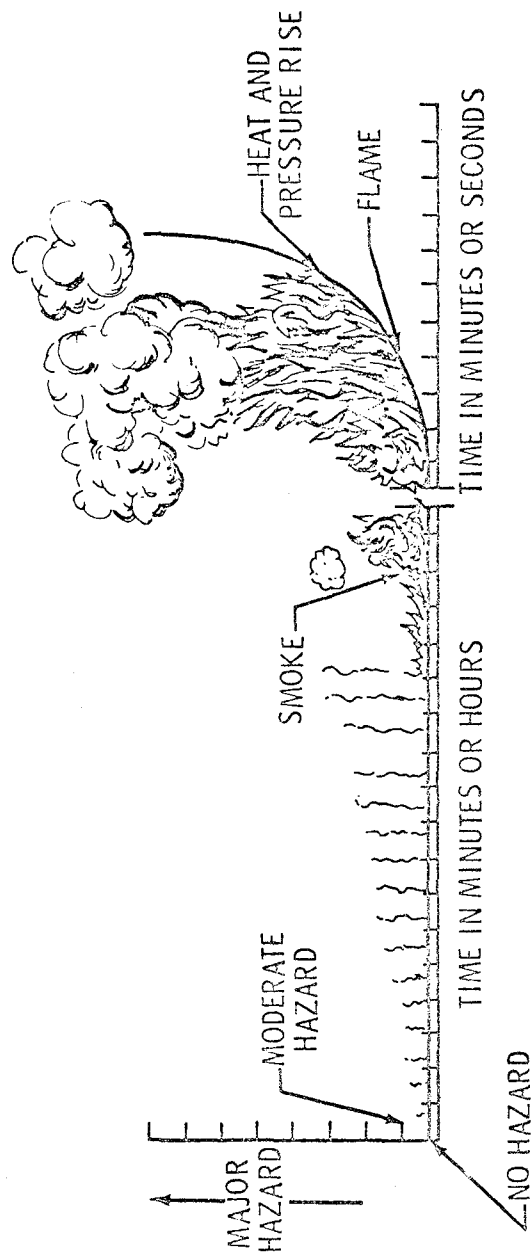


FIGURE 2 -- Typical fire curve.

<u>Factor</u>	<u>Earth</u>	<u>Space</u>
Composition	20% O ₂	20 to 100% O ₂
	15 psia	5 to 15 psia
Propagation rate	---	High in most designs
Toxic effects	Negligible	Serious
Smoke Effects	Appreciable	Very serious
Temperature	Negligible	Catastrophic
Burst Pressure	Negligible	Catastrophic
Escape	Normally excellent	Very limited
System Consequences	Normally survivable	Normally critical to life

Figure 3. Comparative Considerations of Fire Risks in Space vs Earth

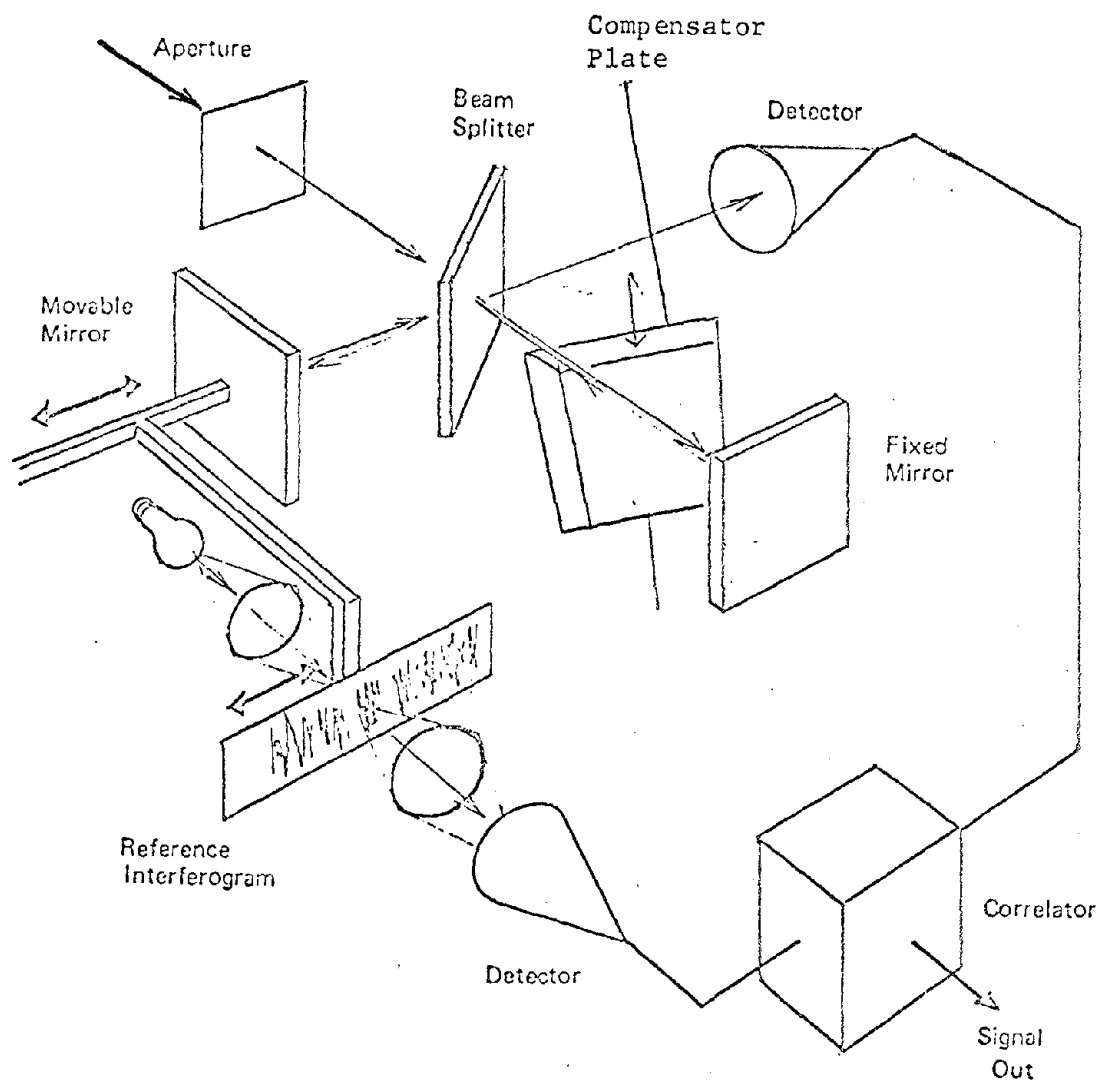


FIGURE 4. - SCHEMATIC DIAGRAM OF CORRELATION INTERFEROMETER

the correlation gas filter concept. However, since the weak points of the gas filters are the same as those inherent with the non-dispersive infrared system, namely background rejection, we would have to circumvent this problem by some means. Since the requirement of background rejection is of utmost importance, the instrument must be based on the use of spectral fine structure whose Lorentz line half widths are on the order of 0.1 cm^{-1} or greater. Also in order for the high resolution instrument to be capable of separating distinguishing features, the gases selected must have vibrational mode with low moments of inertia.

Fortunately, some information can be gleaned on the pyrolysis products of materials selected for Shuttle interior. From this information, we were able to select eight potential candidates to use as incipient fire precursors (Figure 5). Of the eight potential candidates as based upon high resolution spectra and a tentative evaluation of possible interfering gas spectra, it appears that the leading candidates to be used are COF_2 and SiF_4 . However, monitoring these two gases only, will not suffice due to some minor interferences. In order to rely on the data we will have to monitor the background for CO_2 and H_2O in the case of COF_2 and CO in the case of SiF_4 . COF_2 (at 0.6 torr partial pressure) shows resolvable rotational fine structure between 1894 and 1973 cm^{-1} and between 2325 and 2650 cm^{-1} . The average line spacings and half widths are 0.34 cm^{-1} and 0.18 cm^{-1} under an air atmosphere. The line half widths for the pure gas was found to be 0.03 cm^{-1} . SiF_4 has line spacings and Lorentz half widths of 0.50 cm^{-1} and 0.18 cm^{-1} , respectively, under a nitrogen atmosphere in the region between 1917 and 2099 cm^{-1} .

By utilizing a detection system capable of analyzing for the most likely fire precursor or precursors plus those causing background interference, it is believed that a highly reliable incipient fire and toxic gas caution and warning system can be developed for the Shuttle.

Based upon this rationale, we have established some very preliminary parameter goals for our caution and warning system (Figure 6). In addition, the simplest systems would have to provide spectral information without being transformed either to space directly (dispersion) or to space by way of time (interferometry). This can be accomplished by one of three methods; either as a specific spectral filter mask or by negative or positive adsorption filtering. The best approach is the use of the spectral filter mask; however, this not only increases the system complexity, but also degrades its long term reliability.

A simple gas filled optical cell used as an absorption filter for the spectral lines produces what can be called a "negative filter" in the sense

Gas	Suggested Spectral Region (cm^{-1})	Band Strength ($\text{cm}^{-2}\text{atm}^{-1}$ corr. to 25°C)	Line Spacings (cm^{-1})	Line Widths ($\text{cm}^{-1}\text{atm}^{-1}$)
HF	3600-4200 (upper portion of band relatively free of atmospheric interference)	412	40-50	.05-.1
HCl	2500-3100	160	2-25 (smaller spacings of bimodal distribution due to isotopic splittings)	.03-.09
HCN	3200-3400	221	~ 2	---
CH ₄	2800-3200	328	~ 10	---
CO	1900-2300	237	~ 4	.03-.08
NO ₂	2800-3000	61.5	~ 1 and down	---
COF ₂	700-800 (upper portion free of atm interference)	422	$\sim .7$	---
	2400-2500	15.2	---	---

A number of high frequency bands could be used for this molecule if the fine structure can be resolved. Present data indicate this will require resolution of $.1 \text{ cm}^{-1}$ or better. A typical band that could be used if resolved is

Figure 5. Spectral Characteristics of Gases of Interest

Optical Path Length	1 meter
Minimum Detectable Partial Pressure (Typ)	$<10^{-6}$ atm
Spectral Region	As required (probably 2μ - 5μ)
Response Time	<30 seconds
Number of Gases to be Monitored	6 or more
Size, Volume, Weight	Minimum
Lifetime	2 years

Figure 6. Required System Parameters

that it removes the spectral signature of interest while passing all of the background information between the absorption lines. In general, using only negative filtering leads to a system in which the detector/electronic subsystem must discriminate and detect on the basis of very small changes in a large signal (typically changes on the order of 1 part in 10^5 to 10^7 for the problem at hand).

Commercial instruments have been built utilizing such negative filter, but positive filtering concepts have a distinctive advantage. The common implementation of these involves the use of a pneumatic detector that contains the gas of interest. Infrared absorption takes place only at the lines or bands of interest; thus significantly reducing the radiation load on the detector to just the wavelengths of interest.

An alternative approach has been suggested in which "positive filtering" is achieved. In this configuration, the gas sample and the associated optical system pass radiation only in the spectral intervals corresponding to the absorption lines of interest. The system consists of a interferometer which is adjusted so that there is zero path difference in the two arms, and there is destructive interference at the output for all wavelengths, i. e., the interferometer is effectively opaque. Then a sample of the gas of interest is placed in one arm and the anomalous refraction in and near the absorption lines changes one path by many wavelengths. The condition of destructive interference is upset at those wavelengths and radiation passes through the system only at those specific wavelengths. A positive filtering system generally leads to smaller signals, but much larger percentage modulation for detection and discrimination.

If either one of these approaches is used in a simple level detection device, it would be vulnerable to changes in the background level and the presence of spurious absorption bands. Sensitivity to background (or source) level can be completely eliminated and susceptibility to false alarms greatly reduced by combining the two techniques to determine the relative change in absorption of the lines of interest and the spectral region between the lines.

An effective and compact configuration for accomplishing this is shown in Figure 7. The basic positive filter interferometer is set up and the radiation at the wavelengths of the absorption lines appears in the lower output beam. One of the interferometer mirrors is made partially transmitting allowing the "negative filtered" radiation to escape the interferometer. A second gas cell may be necessary to obtain a sufficient amount of negative filtering. In any event, this radiation (upper beam) is passed through an optical attenuator so that its total power exactly equals the positively filtered beam when none of the gas of interest is in the sample path.

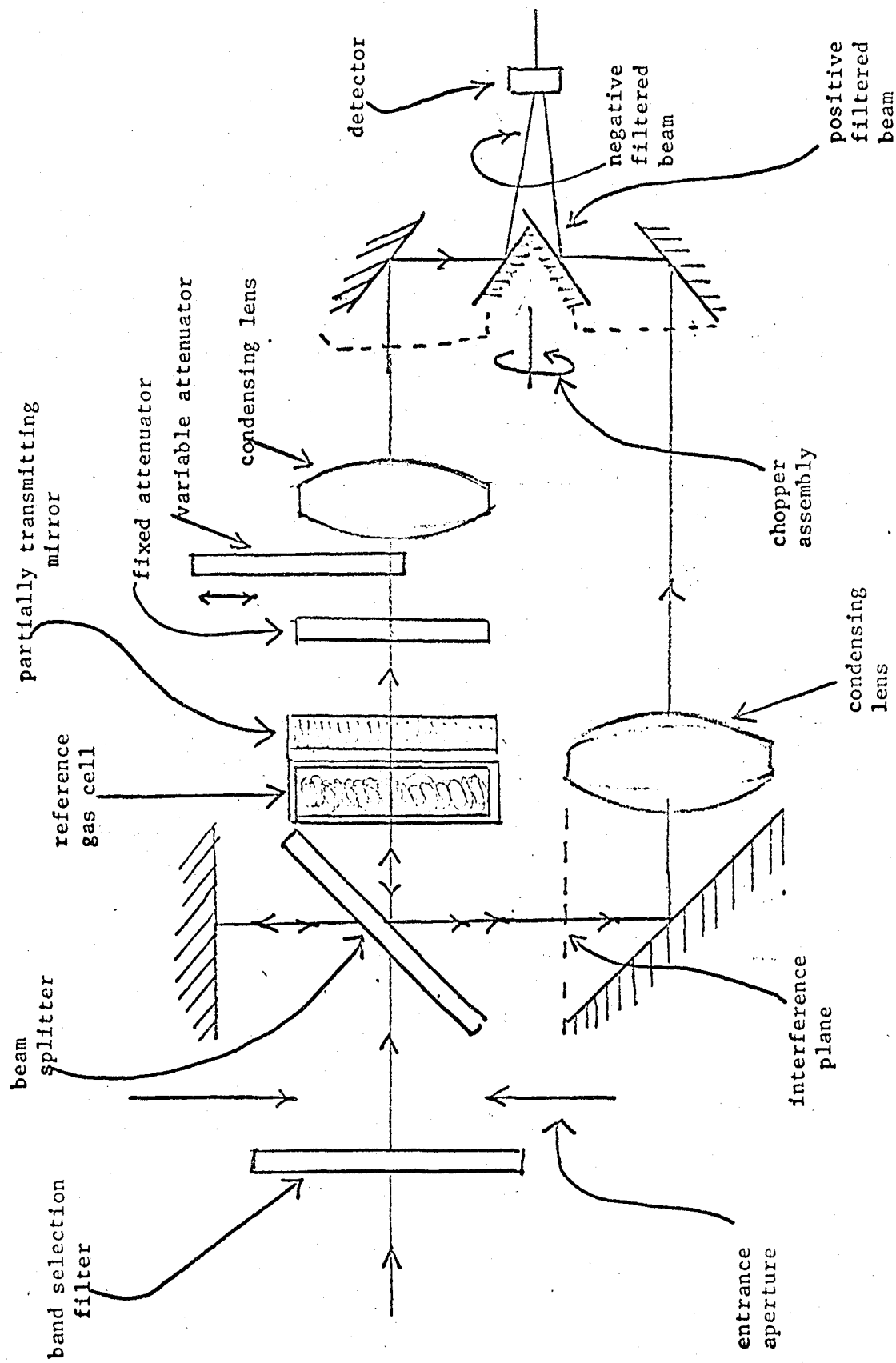


Figure 7. Schematic Layout of Gas Filter Correlating Sensor

The strength of the two beams is compared by alternately directing them to a single detector. A signal processing block diagram is shown in Figure 8. The difference between the two beams is determined by the a.c. portion of the detector signal and the d.c. level is neglected. Synchronous detection of the signal is used with the rotation or a change in broad absorption band which covers both the positively filtered lines and the negatively filtered region, the radiation levels in the two beams change by the same percentage and there is no signal difference introduced. Positive signals (in phase) indicate the radiation in the absorption bands has fallen off and the gas of interest is present. Negative signals indicate that something in the background between the absorption lines of interest is beginning to absorb. This negative signal would be nulled out either optically (by varying the attenuator), or electrically to preserve the threshold setting of the alarm. Interruption of the beams or a gross loss in transmission from the source would be used to sound an "inoperative" alarm.

If there were interfering gases in the background, i.e., gases with absorption lines overlapping those of the gas of interest, the blocking filter at the sensor input could include negative filtering by a cell filled with the offending gas.

In the present stage of development, we now have an engineering breadboard in operation (Figure 9) and testing is now underway to determine its sensitivity (signal to noise ratio), stability, specificity and susceptibility to interference, nature of the stored reference, capability of being used in multigas analysis, and equipment complexity. Gas sampling techniques and capabilities are also being evaluated as well. One technique is obviously by use of a finite dimensional gas cell where samples from a given "black box" or locale can be assayed. The second concept is to evaluate the ability of the unit to be used for area monitoring. If the second concept is found to be feasible two correlation gas filters can be used for the purpose of triangulating in on a potential fire source.

The contemplated flight unit based upon present estimates will be modular in nature. Each module will be approximately 5 cm² by 15 cm long. Six modules are expected to make up the total package.

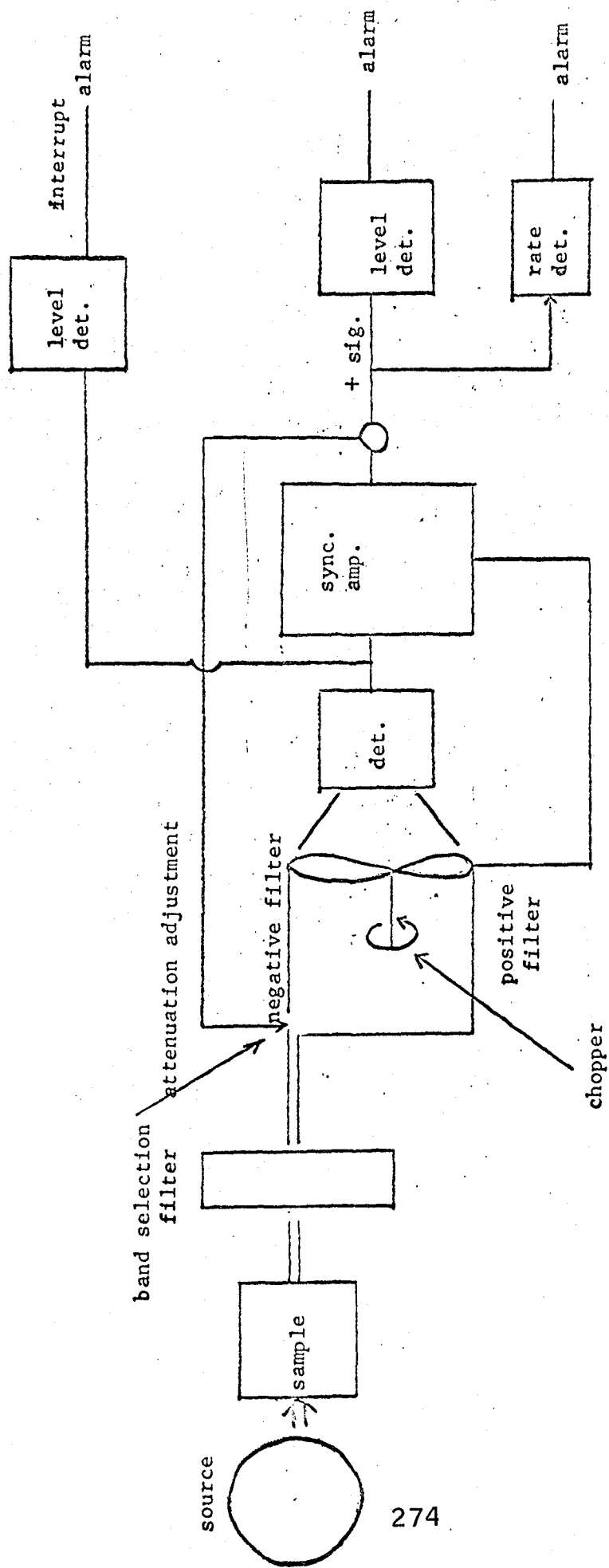


Figure 8. Block Diagram of Gas Filter Cell Instrument

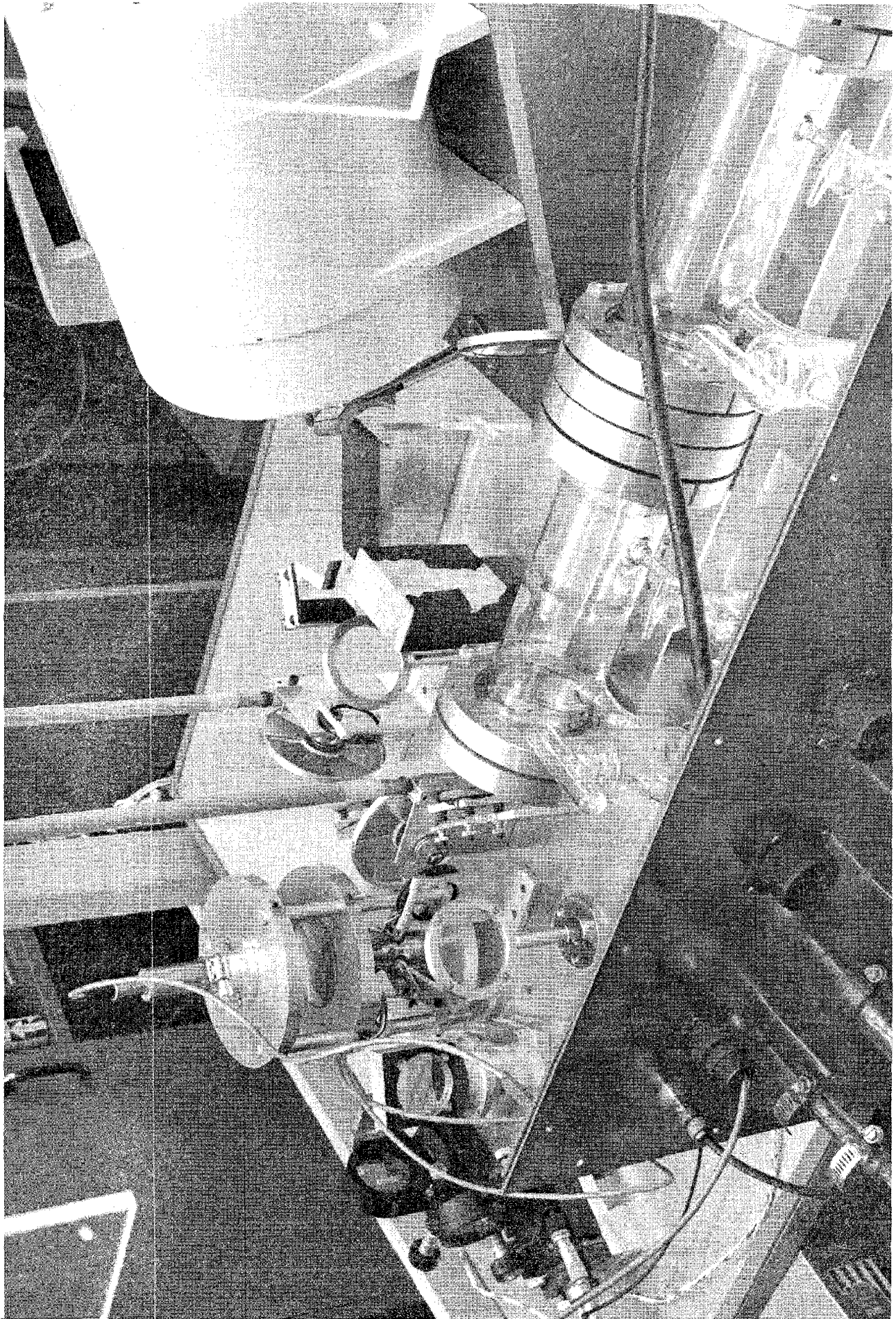


Figure 9. Engineering Breadboard Model of a Gas Filter Cell Instrument

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Conclusions

Based upon present evidence, the gas filter cell offers the ultimate in background rejection. Not only does the gas filter cell offer sensitivity as good as the other systems, but its inherent throughput advantage offers more ultimate sensitivity at the expense of some source power. The most difficult problem in implementing the gas filter cell is making stable reference samples for the two-year lifetime. It is believed that the individual gas cell sensor can be made into a small, compact, and reliable instrument. However, multiple gas monitoring will probably require parallel optical systems.

Based upon present data, the amount of toxic gas required to implement the system will be insufficient to be a significant hazard in the spacecraft. Also, this approach is believed to offer the most convenient changes in gas of interest - simply add a sensor for the new species without changing any of the existing system.

FIRE PROTECTION DESIGN FOR SHUTTLE

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I. INTRODUCTION

A. The objectives of the fire protection systems at KSC are, in order of priority:

1. Protection of personnel.
2. Protection of facilities.
3. Protection of flight hardware.

B. Specific restrictions to systems are:

1. There will be no automatic activation of water systems capable of spraying on flight hardware except where the system should be intentionally armed for automatic operation during a specific set of circumstances or conditions.

2. Two manual operating functions, with logic to prevent inadvertent operation, will be required to turn the water on.

3. Separate electrical circuitry between operating switches and valves should be provided so as to prevent inadvertent activation by a single electrical short.

II. SHUTTLE FLOW THROUGH THE FACILITIES (Figure 1)

A. Vehicle Assembly Building (Figure 2)

1. Assembly of Major Structural Elements
2. Test and Checkout of Flight Systems
3. Mating and Checkout
4. Component or System Overhaul and Maintenance

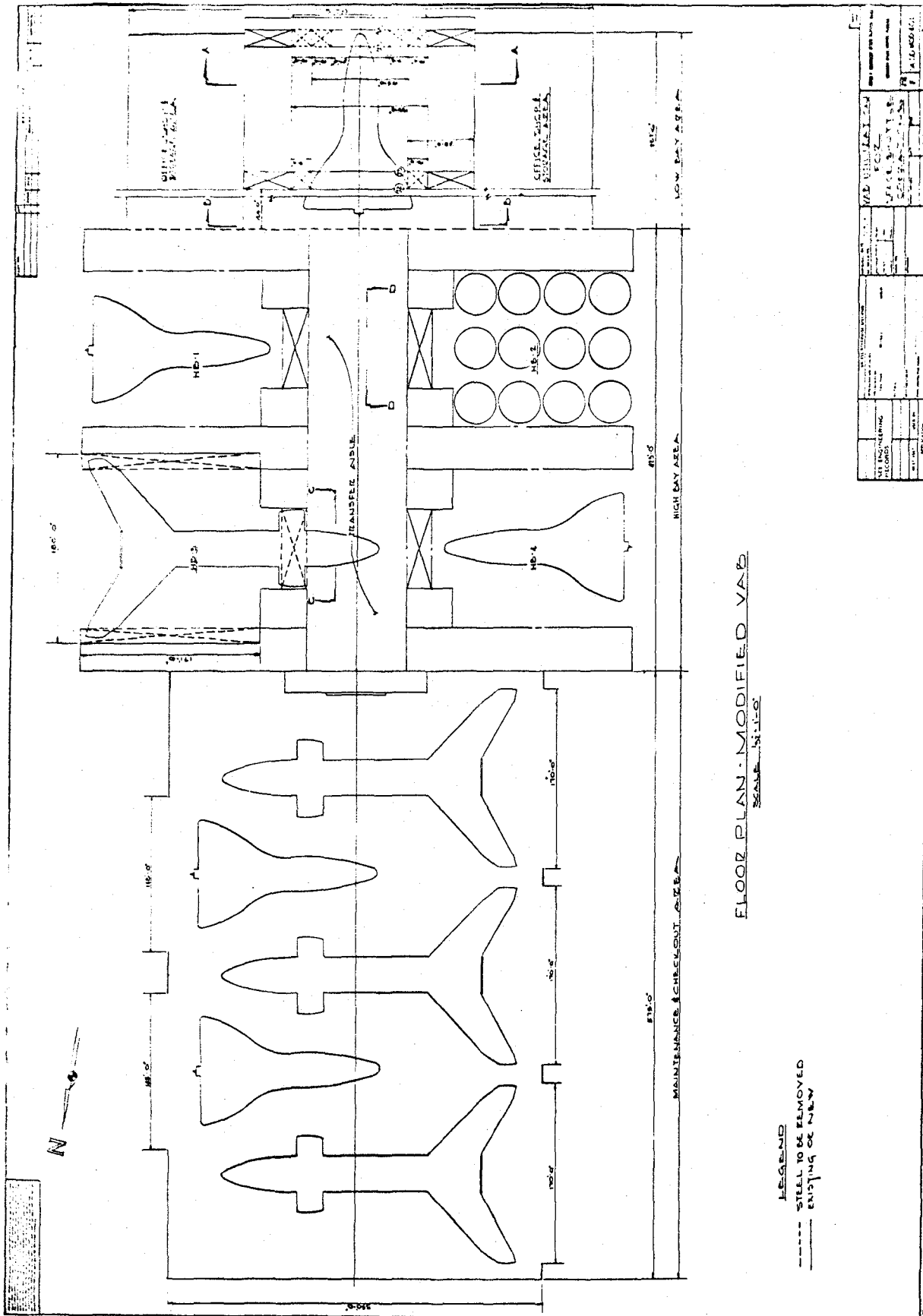
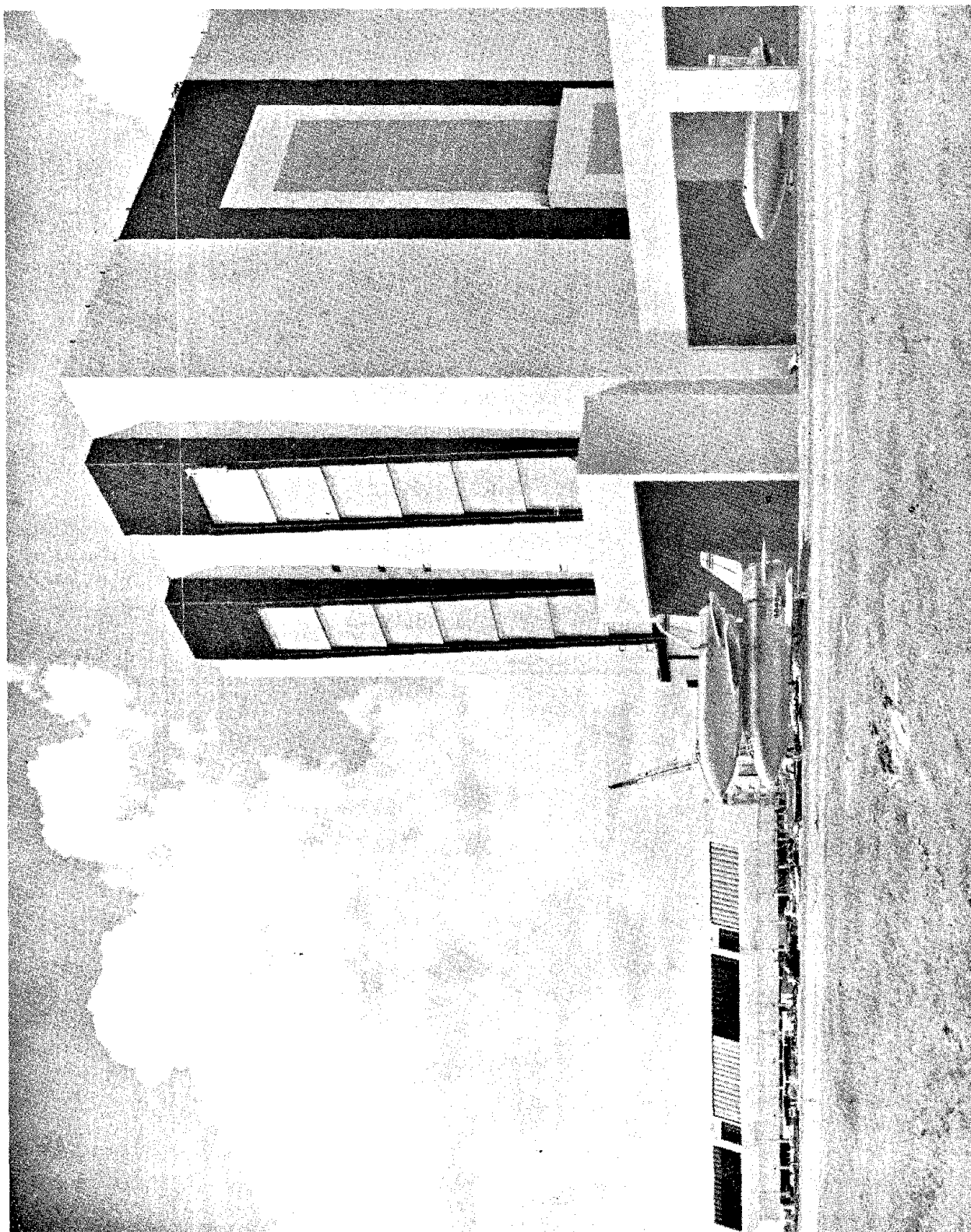


Figure 1. Shuttle Flow through Facilities



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Figure 2. KSC - VAB WITH ADDITION TO NORTH END - HORIZONTAL
TO PAD TRANSPORT

B. Launch Pad (Figure 3)

1. System Preparation & Test
2. CDDT
3. Propellant and Cryo Loading
4. Launch Countdown

C. Landing Area (Includes air-breather engine run up) (Figure 4)

D. Safing Area (Figure 4)

1. Venting, LOX and GH_2
2. Purging and Passifying Systems
3. Loading JP Fuel
4. Cargo and Crew Off-loading

III. SYSTEMS AVAILABLE - HAZARD RELATIONSHIP

A. Vehicle Assembly Building

1. This building is part sprinklered. Sprinkler protection has been provided for combustible and flammable storage areas.
2. The extensible platforms in the High Bays are protected by open nozzle deluge systems. These systems have three modes of operation: automatic, manual, and off.
3. The existing systems provide protection against a fire from gaining such proportions as to seriously expose ordnance to excessive temperatures with possible explosion.
4. A new spill (JP) containment, drain, disposal and water wash-down should be provided. Dikes with removable sections for traffic flow should be provided.
5. Certain inaccessible densely loaded compartments of the shuttle stages should be designed to receive an extinguishing and/or inerting media. The media has not been selected. Portable equipment should be connected and ready to support during test and checkout.

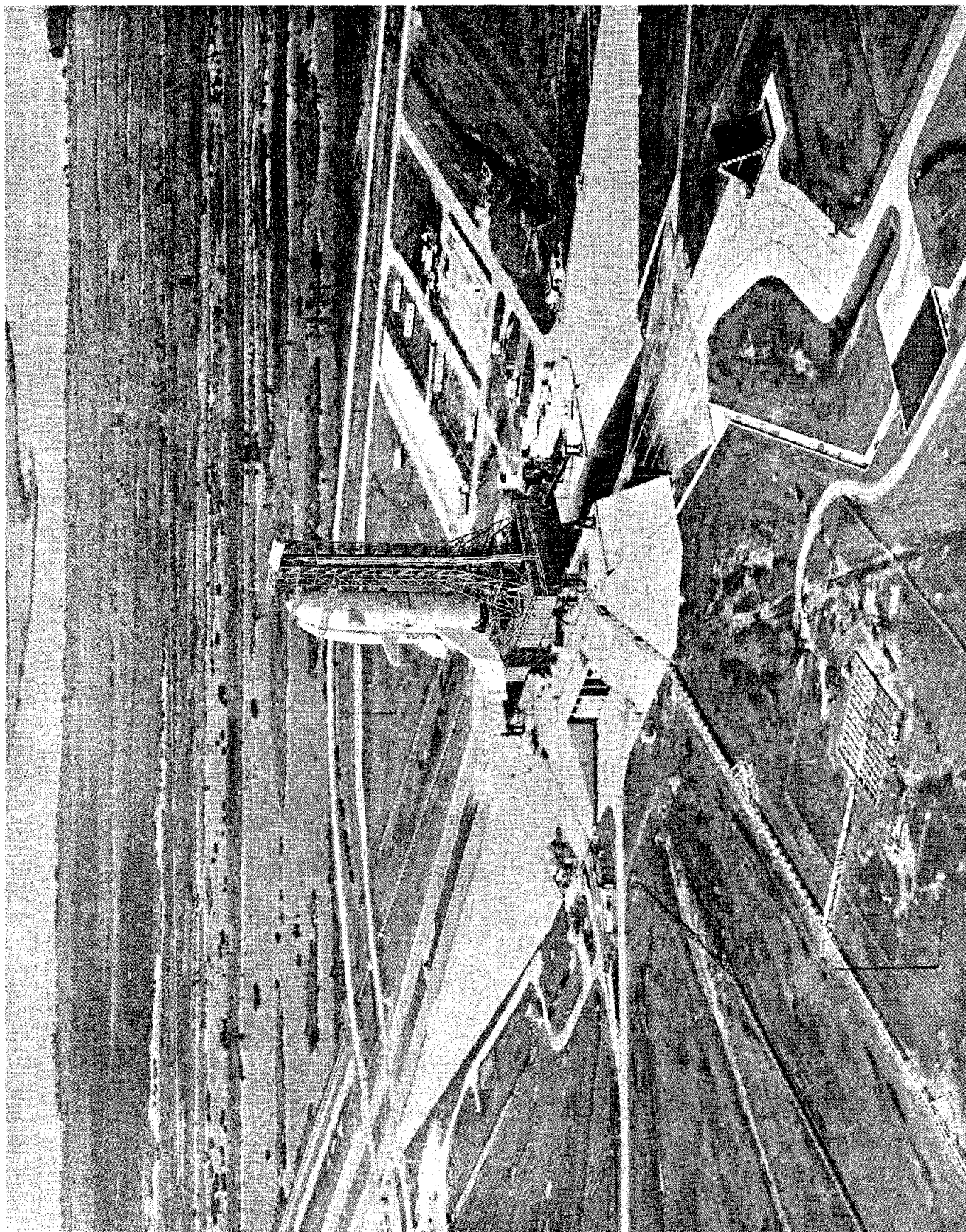


Figure 3. LAUNCH PAD 39 WITH SHUTTLE ON MOBILE LAUNCH
VERTICAL TRANSPORT TO PAD CONCEPT

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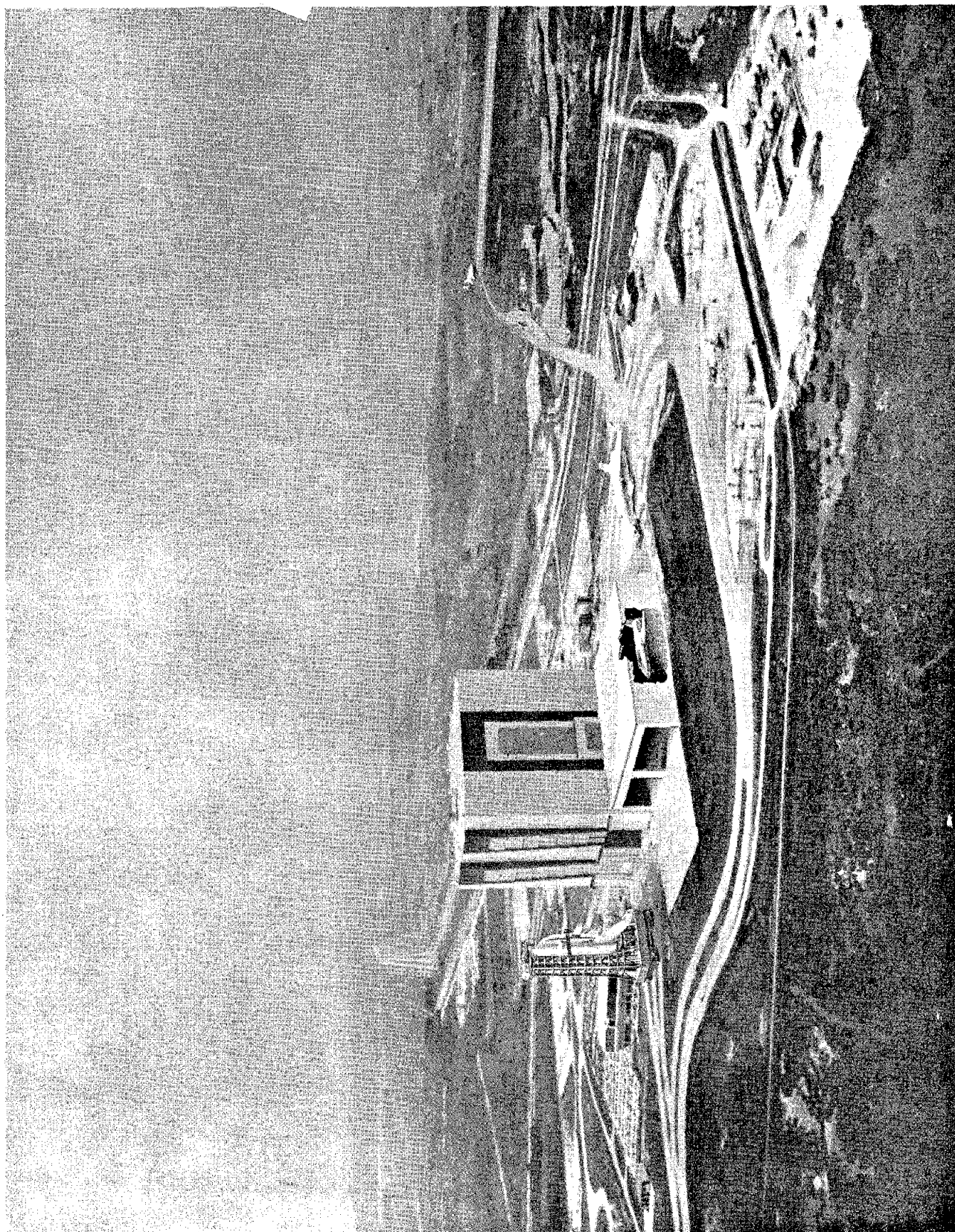


Figure 4. KSC - VAB WITH ADDITION TO NORTH END - VERTICAL
TRANSPORT TO PAD

B. Launch Pad (Base Line - Vertical Concept)

1. The Launch Umbilical Tower (LUT) has open nozzle water deluge systems on approximately 50% of the work levels plus the egress paths.
2. The existing systems will be modified as necessary to provide protection at the required shuttle work levels.
3. An additional egress route will be established and protected with open nozzle water spray.
4. As stated previously, portable equipment will be connected to the flight hardware compartments and placed in a ready to support mode during periods of hazardous operations.
5. With our existing Single Failure Point philosophy and a change to simultaneous flow of LH₂ and LOX, the fire protection systems will be designed to contain and/or extinguish a fire. Reducing the probability of an explosion is a separate subject.
6. Related to fire protection is response time and procedures of the fire fighting and rescue personnel. New concepts for the rescue of sixteen (16) crew and passengers will have to be developed based on final configuration of and access to the shuttle stages. The existing slidewire and elevators will require modification if they are retained.

C. Landing Area

1. Mobile equipment will be used to provide a 2" thick layer of protein foam on the runway. Additional mobile foam equipment will be available for covering the shuttle stage wherever it stops if required. This same equipment will then be available for protection at other locations during ground cycle.
2. Water pumper units will be provided.
3. Halon 2402, Dibromotetrafluoroethane, CBrF₂CB₂F₂ has possibilities for outdoor use and will be considered.

D. Safing Area

1. An installed protein foam system is highly recommended. Some of the discharge nozzles will be directionally controlled.
2. A water deluge system will be provided which can also be used for cooling or wash down.

IV. The extinguishing media that will be considered are:

A. Water and Water Additives

B. Foam

1. Hi Expansion

2. Protein

3. Light Water

C. Gaseous

1. Nitrogen

2. CO₂

3. Halon 1301 and 2402

D. Dry Powder